leachate collection system. After the landfill has been filled to capacity, a 3-foot clay cover is installed and covered with 1 foot of loam to support vegetation and drainage. The hydraulic conductivity of both the liner and cover clays is assumed to be $1x10^{-7}$ cm/sec, the typical design specification for compacted clay liners (U.S. EPA, 1988c).

In the composite liner scenario, wastes are placed on a liner system that consists of a 60 mil HDPE membrane with either an underlying geosynthetic clay liner or a 3-foot compacted clay liner. A leachate collection system is also assumed to exist between the waste and the liner system. After the landfill has been filled to capacity, a 3-foot clay cover is assumed to be installed and covered with 1 foot of loam to support vegetation and drainage (U.S. EPA, 2002b).

As described in Section 3.2.3 (and Appendix B), one of these three liner types was assigned to each CCW landfill or surface impoundment modeled based on the liner type data from the 1995 EPRI Survey (EPRI, 1997).

3.2.2 Modeling Approach and Assumptions

The starting point for the landfill source-term model simulation is the time when the landfill is closed (i.e., when the unit is filled with CCW).[5] As described in detail below, the full-scale analysis modeled contaminants leaching from CCW into precipitation infiltrating the landfill, which exits the landfills as leachate. Contaminant loss in leachate was taken into account at closure by subtracting the cumulative amount of contaminant mass loss that occurred during the unit's active life from the amount of contaminant mass present at the time of landfill closure. Loss calculations in the landfill source-term model continue after closure until the contaminant is depleted from the waste mass in the landfill. This is a conservative assumption, as some metal will not leach from the waste mass.

Infiltration and Leaching

The average rate at which water percolates through the landfill over time (the long-term infiltration rate) drives the leaching process in the landfill, which results from partitioning of the constituent from the waste into the infiltrating water. The methodology, assumptions, and data used to determine infiltration rates for each CCW liner scenario are consistent with the approach used in EPA's Industrial D guidance, as described in Section 4.3 and Appendix A of the *EPACMTP Parameter/Data Background Document* (U.S. EPA, 2003a) and Section 4.2.2 of the *Industrial Waste Evaluation Model (IWEM) Technical Background Document* (U.S. EPA, 2002b). EPA developed the IWEM model as part of a guide for managing nonhazardous industrial wastes in landfills and surface impoundments (http://www.epa.gov/industrialwaste). To help ensure that it was technically sound, the model (including the liner scenarios and algorithms used in the CCW risk assessment) was developed with a large stakeholder working group, including representatives from industry. The model was also subjected to a peer review in 1999 (64 FR 54889–54890, October 8, 1999, *Peer Reviews Associated With the Guide for*

[5] The simple landfill model used in this assessment cannot model a landfill as it is being filled prior to closure. Although leaching does occur during a landfill's operating life, risks from these releases are insignificant when compared to postclosure releases, given the long time it takes metal-bearing wastes to leach and reach peak concentrations in groundwater wells surrounding the landfill. EPA does not believe that the additional risks from the preclosure period justify the additional complexity, data, and effort required to model an operating landfill.

Industrial Waste Management), and the model was updated and improved in response to those comments before its final release in 2003. That update included the addition of a more robust liner leakage database to support the existing algorithms for calculating infiltration rates through composite liner systems.

No-Liner (Unlined) Scenario. For the no-liner scenario, infiltration rates were selected from a database in EPACMTP that contains 306 infiltration rates already calculated using EPA's Hydrologic Evaluation of Landfill Performance (HELP) water balance model (Schroeder, et al., 1994a, 1994b). HELP is a product of an interagency agreement between EPA and the U.S. Army Corps of Engineers Waterways Experiment Station, and was subjected to the Agency's peer and administrative review. All of the infiltration rates were calculated based on the single typical landfill design described in Section 3.2.1, with the only variables that change between HELP simulations being the meteorological data associated with 102 nationwide climate centers and the type of cover soil applied at closure. Three cover soil categories representing coarse-grained soils, medium-grained soils, and fine-grained soils were used. The selection of an infiltration rate from the database depends on the type of cover soil selected for the landfill and the assignment of the landfill to a HELP climate center. The unlined HELP-derived infiltration rates are presented in U.S. EPA (2003a) by climate center. The assignment of HELP climate centers and soil categories to each CCW site modeled is described in Appendix C.

Clay Liner Scenario. The clay liner scenario is very similar to the unlined scenario in that previously calculated HELP infiltration rates for a single clay-lined, clay-capped landfill design were used. The scenario is based on a typical engineered compacted clay liner that is 3 feet thick with a design hydraulic conductivity of $1x10^{-7}$ cm/sec. The one difference from the unlined case is that the clay liner and cover control the rate of water percolation through the landfill and thus infiltration rate does not vary with cover soil (i.e., there is one clay liner infiltration rate per climate center). The clay liner HELP-derived infiltration rates are provided in U.S. EPA (2003a).

Composite Liner Scenario. Composite liner infiltration rates are compiled from monthly average leak detection system (LDS) flow rates for industrial landfill cells reported by TetraTech (2001). The liner configurations are consistent with the composite liner design assumptions presented in Section 3.2.1 and are the same as those assumed for defaults in EPA's Industrial D landfill guidance (U.S. EPA, 2002b). The LDS flow rates were taken from 27 municipal landfill cells and used in the IWEM model (U.S. EPA, 2002b). As shown in Table 3-2, these LDS flow rates include 22 operating landfill cells and 5 closed landfill cells located in eastern United States: 23 in the northeastern region, 1 in the mid-Atlantic region, and 3 in the southeastern region. Each of the landfill cells is underlain by a geomembrane/geosynthetic clay liner which consists of a high-density polyethylene geomembrane of thickness between 1 and 1.5 mm, overlying a 6-mm composite geosynthetic clay layer consisting of two geotextile outer layers with a uniform core of bentonite clay to form a hydraulic barrier. Each liner system is underlain by an LDS.

As described in U.S. EPA (2002b), only a subset of the TetraTech (2001) flow rates were used to develop the composite liner infiltration rates. LDS flow rates for geomembrane/ compacted clay composite-lined landfill cells were not used in the distribution because compacted clay liners (including composite geomembrane/compacted clay liners) can release

water during consolidation and contribute an unknown amount of water to LDS flow, which makes it difficult to determine how much of the LDS flow is due to liner leakage versus clay consolidation. Also, LDS flow rates from three geomembrane/geosynthetic clay lined-cells were not used. For one cell, postclosure flow rates were very high, and were more than twice as high as those recorded during the cell's operating period. Data were not used for two other cells because of inconsistencies with the data for the 27 landfill cells used to develop composite liner infiltration rates (U.S. EPA, 2002b). The composite liner infiltration rates were specified as an empirically distributed input to the landfill model (see U.S. EPA ,2003a).

Table 3-2. Leak Detection System Flow Rate Data Used to Develop Landfill Composite Liner Infiltration Rates

Cell ID	Status	Flow rate (m/y)	Location
G228	Operating	2.1E-04	Mid-Atlantic
G232	Operating	4.0E-04	Northeast
G232	Closed	7.3E-05	Northeast
G233	Operating	0	Northeast
G233	Closed	0	Northeast
G234	Operating	7.3E-05	Northeast
G234	Closed	0	Northeast
G235	Operating	1.5E-04	Northeast
G235	Closed	3.7E-05	Northeast
G236	Operating	3.7E-05	Northeast
G236	Closed	0	Northeast
G237	Operating	7.3E-05	Northeast
G238	Operating	0	Northeast
G239	Operating	7.3E-05	Northeast
G240	Operating	0	Northeast
G241	Operating	0	Northeast
G242	Operating	0	Northeast
G243	Operating	0	Northeast
G244	Operating	0	Northeast
G245	Operating	0	Northeast
G246	Operating	0	Northeast
G247	Operating	0	Northeast
G248	Operating	0	Northeast
G249	Operating	7.3E-05	Northeast
G250	Operating	2.2E-04	Southeast
G251	Operating	0	Southeast
G252	Operating	0	Southeast

Source: U.S. EPA (2002a); original data from TetraTech (2001).

Source Depletion and Mass Balance

For this assessment**,** the landfill source-term model represents releases from landfills as a finite source where the mass of a constituent in a landfill is finite and depleted over time by

leaching. The landfill source-term model is set as a pulse source, where the leachate concentration is constant over a prescribed period of time and then goes to zero when the constituent is depleted from the landfill. A pulse source is appropriate for metals and other constituents whose sorption behavior is nonlinear. Because all but one (nitrate/nitrite) of the constituents addressed in the full-scale analysis are metals, releases from landfills were modeled as pulse sources.

For a pulse source, basic mass balance considerations require leaching from the landfill to stop when all of the constituent mass has leached from the landfill. For the constant concentration pulse source condition, the pulse duration is given by

$$TSOURC = \frac{CWASTE \times DEPTH \times FRACT \times CTDENS}{CZERO \times SINFIL} \tag{3-1}$$

where

TSOURC	=	Pulse duration (yr)
CWASTE	=	Constituent concentration in the waste (mg/kg)
DEPTH	=	Depth of landfill (m)
FRACT	=	Volume fraction of the landfill occupied by the waste (unitless)
CTDENS	=	Waste density (g/cm^3)
CZERO	=	Initial waste leachate concentration (mg/L)
SINFIL	=	Annual areal infiltration rate (m/yr).

The landfill source-term model uses the above relationship to determine the leaching duration. More details regarding the waste concentration and WMU parameters in Equation 3-1 are provided below and in Appendices A and B.

3.2.3 Landfill Model Input Parameters

Input parameters required by the landfill source-term model are discussed below. Additional details on how data for these inputs were collected for the CCW risk assessment are provided in Appendix A for leachate and waste concentrations and Appendix B for landfill dimensions and characteristics.

- **Landfill Area.** The model uses landfill area to determine the area over which infiltration rate occurs and, along with landfill depth and waste concentration, to calculate the total contaminant mass in the landfill. CCW landfill area data were obtained from the EPRI comanagment survey (EPRI, 1997). The landfill was assumed to be square.

- **Landfill Depth.** Landfill depth is one of several parameters used by the landfill source-term model to calculate the contaminant mass in the landfill. For CCW landfills, average waste depth was estimated by dividing landfill capacity by landfill area. CCW landfill capacity data were taken from the EPRI comanagement survey (EPRI, 1997).

- **Depth Below Grade.** The depth of the bottom of the landfill below the surrounding ground surface is used, along with depth to groundwater, to determine the thickness of the unsaturated zone. For CCW landfills, depth below grade was determined from a national distribution based on available measurements from a number of CCW landfills (see Appendix B).

- **Waste Fraction.** The landfills were assumed to be CCW monofills, which corresponds to a waste fraction of 1.0.

- **Waste Density.** The average waste bulk density, as disposed, is used to convert waste volume to waste mass. The waste bulk density for all CCW waste types was assumed to be 1.19 g/cm^3 (U.S. EPA, 1998b).

- **Leachate Concentration.** The concentration of waste constituents in leachate was assumed to be constant until all of the contaminant mass initially present in the landfill has leached out, after which the leachate concentration was assumed to be zero. The constant value used for leachate concentration is from EPA's CCW Constituent Database, described in Appendix A.

- **Waste Concentration.** In the finite-source scenario modeled, the total waste concentration is used, along with the waste bulk density and landfill area and depth, to determine the total amount of a constituent available for leaching. Measured total CCW concentrations were paired with leachate concentrations, as described in Appendix A and provided in Attachment A-2.

- **Liner Type.** The type of liner is used to determine the infiltration/leaching scenario used to calculate leachate flux from the landfill. Table 3-3 shows the crosswalk used to assign one of the three liner scenarios to each facility based on the liner data in the 1995 EPRI survey (EPRI, 1997). Attachment B-2 to Appendix B provides these assignments, along with the original EPRI liner type, for each CCW landfill facility modeled. One significant uncertainty in these liner assumptions is how representative the EPRI survey data are of current conditions at coal combustion facilities.

Table 3-3. Crosswalk Between EPRI and CCW Source Model Liner Types

EPRI Liner Type	Model Liner Code	Description
Compacted ash	0	no liner
Compacted clay	1	clay
Composite clay/membrane	2	composite
Double	2	composite
Geosynthetic membrane	2	composite
None/natural soils	0	no liner

3.2.4 Model Outputs

For each year in the simulation, the landfill source-term model uses the average annual leachate concentration and infiltration rate to calculate a constituent flux through the bottom of the landfill. This time series is used as an input for the EPACMTP unsaturated zone model.

3.3 Surface Impoundment Model

Releases from surface impoundments were modeled using a surface impoundment source-term model contained in EPACMTP. An overview and statement of assumptions for the surface impoundment model is presented here, followed by a listing of inputs to the surface impoundment source-term model and a brief discussion of the output generated by the model. The primary differences between the treatment of landfills and surface impoundments are (1) the integration of the surface impoundment source term into the unsaturated flow solution, and (2) clean closure of the impoundment after the operating period is over.

3.3.1 Conceptual Model

The surface impoundment model treats a surface impoundment as a temporary WMU with a prescribed operational life. Unlike the landfill model, clean closure is assumed; that is, at the end of the unit's operational life, the model assumes that all wastes are removed and there is no further release of waste constituents to groundwater. Although this simplifying assumption limits the length of potential exposure, and is not consistent with the practice to close CCW surface impoundments with these wastes in place, the peak annual leachate concentrations on which the CCW risk results are based are not likely to be affected, because they are highest when the surface impoundment is in operation.

Following the unit's closure, the surface impoundment model assumes that the contaminated liquid and sediment in the surface impoundment are replaced by uncontaminated liquid and sediment with otherwise identical configurations and properties. The contaminants that have migrated to the unsaturated zone during operation continue to migrate towards the water table with the same infiltration rate as during operation. By continuing infiltration after the wastes are removed, the infiltration through the surface impoundment unit can be modeled as a single steady-state flow regime until concentrations in groundwater are no longer affected by constituents released from the surface impoundment during its operation.

The EPACMTP surface impoundment model assumes a square footprint and a constant ponding depth during the impoundment's operational life (Figure 3-5). For an unlined impoundment, the model assumes that while the impoundment is in operation, a consolidated layer of sediment accumulates at the bottom of the impoundment. The leakage (infiltration) rate through the unlined impoundment is a function of the ponding depth in the impoundment and the thickness and effective permeability of the consolidated sediment layer at the bottom of the impoundment. The rate of leakage is constrained to ensure that there is not a physically unrealistic high rate of leakage, which would cause groundwater mounding beneath the unit to rise above the ground surface. Underlying the assumption of a constant ponding depth, the surface impoundment source-term model assumes that wastewater in the impoundment is continually replenished while the impoundment is in operation. It also assumes, from the

beginning of the unit's operation, that the sediment is always in equilibrium with the wastewater (i.e., the presence of sediment does not alter the concentration of leachate). Accordingly, the surface impoundment source-term model also assumes that the leachate concentration is constant during the impoundment operational life. Typically, the leachate concentration is equal to the concentration in the wastewater entering the impoundment.

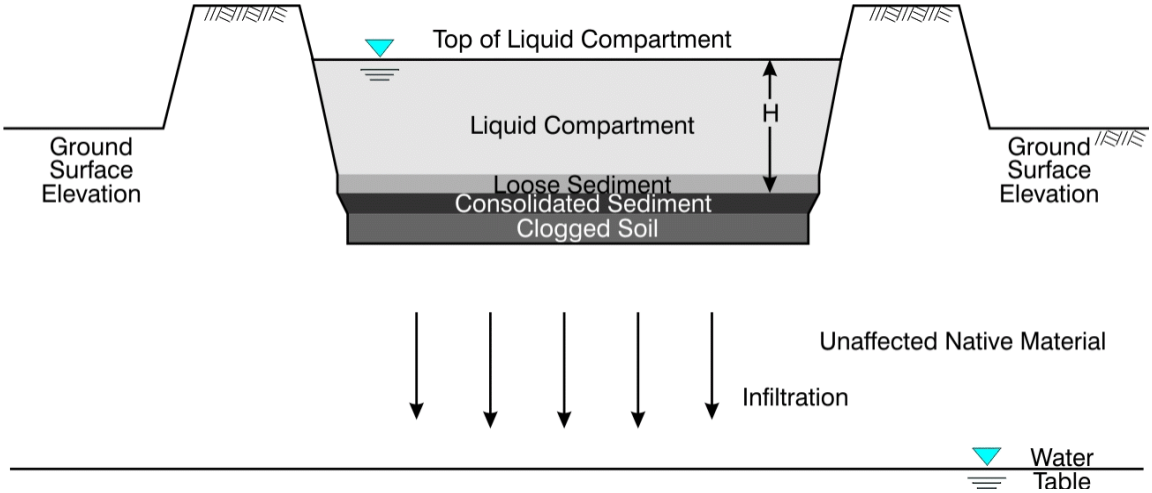


Figure 3-5. Schematic cross-section view of surface impoundment.

Three liner scenarios were modeled: a no-liner (unlined) scenario, a compacted clay liner, and a composite liner.

In the unlined scenario, wastewater is placed directly on local soils and the depth of water is constant over the entire life of the impoundment, pre- and post-closure. As described above, sediments accumulate and consolidate at the bottom of the impoundment and migrate into the underlying native soils, where they clog pore spaces and provide some barrier to flow. The surface impoundment model assumes that the thickness of the consolidated sediments is equal to one-half of the total sediment thickness, which is an input to the model. The sediment thickness was assumed to be 0.2 m for all simulations. The model also assumes that the thickness of the clogged region of native soils is always 0.5 m and has a hydraulic conductivity 10 percent of that of the native soil underlying the impoundment.

In the clay liner scenario, wastewater is placed on a compacted clay liner, which is installed on the local soils. The assumptions for an unlined impoundment also apply to the compacted clay liner scenario, except that a compacted clay liner filters out the sediments that clog the native soils in the unlined case, so the effect of clogging the native materials is not included in the calculation of the infiltration rate. The thickness of the compacted clay liner was assumed to be 3 feet and the hydraulic conductivity was assumed to be $1x10^{-7}$ cm/sec (U.S. EPA, 1988c).

In the composite liner scenario, wastewater is placed on a synthetic membrane with an underlying geosynthetic or natural compacted clay liner with a hydraulic conductivity of $1x10^{-7}$ cm/sec. The membrane liner was assumed to have a number of pinhole leaks of uniform size

(6 mm^2). The distribution of leak densities (expressed as number of leaks per hectare) was compiled from 26 leak density values reported in TetraTech (2001), the best available data on liner leaks. These leak densities are based on liners installed with formal construction quality assurance (CQA) programs. The 26 sites with leak density data are mostly located outside the United States: 3 in Canada, 7 in France, 14 in the United Kingdom, and 2 in unknown locations; we assume that these are representative of U.S. conditions. The WMUs at these sites (8 landfills, 4 surface impoundments, and 14 of unknown type) are underlain by a layer of geomembrane with a thickness varying from 1.14 mm to 3 mm. The majority of the geomembranes (23 of 26) are made from HDPE, and the remaining 3 are made from prefabricated bituminous geomembrane or polypropylene. One of the sites has a layer of compacted clay liner beneath the geomembrane; however, for 25 of the 26 sites, material types below the geomembrane layer are not reported. The empirical distribution used in the analysis can be found in IWEM (U.S. EPA, 2002b), along with a table showing details about the 26 liners used to develop the distribution.

3.3.2 Modeling Approach and Assumptions

Figure 3-5 illustrates a compartmentalized surface impoundment with stratified sediment. Shown in the figure are the liquid compartment, the sediment compartment (with loose and consolidated sediments), and the unsaturated zone (with clogged and unaffected native materials). The model assumes that all sediment layer thicknesses remain unchanged throughout the life of the unit.

The EPACMTP surface impoundment model uses the unsaturated zone flow model to calculate the infiltration rate out of the bottom of the impoundment. This model is designed to simulate steady-state downward flow through an unsaturated (vadose) zone consisting of one or more soil layers. Steady-state means that the rate of flow does not change with time. In the case of flow out of an unlined surface impoundment, the model simulates flow through a system consisting of three layers: a consolidated sediment layer, a clogged soil layer, and a native soil layer.

The native unsaturated soil extends downward to the water table. The steady-state infiltration rate out of the surface impoundment is driven by the head gradient between the water ponded in the impoundment and the head at the water table. The pressure head at the top of the consolidated sediment layer is equal to the water depth in the impoundment plus the thickness of the unconsolidated sediment.

The *EPACMTP Technical Background Document* (U.S. EPA, 2003c) describes the algorithms used in this model to calculate the infiltration rate from surface impoundment units, and discusses in detail the maximum allowable infiltration rate based on the groundwater mounding condition. This information is summarized here.

The EPACMTP surface impoundment source-term model calculates infiltration through the accumulated sediment at the bottom of an impoundment, accounting for clogging of the native soil materials underlying the impoundment, liner conditions, and mounding due to infiltration. The modeled infiltration is governed by the depth of liquid in the impoundment and the following limiting factors:

- **Effective hydraulic conductivity and thickness of the consolidated sediment layer.** As sediment accumulates at the base of the impoundment, the weight of the liquid and upper sediments tends to compress (or consolidate) the lower sediments. The consolidation process reduces the hydraulic conductivity of the sediment layer, and the layer of consolidated sediment will act as a restricting layer for flow out of the impoundment. By contrast, the layer of loose, unconsolidated sediment that overlies the consolidated sediment layer is assumed not to restrict the flow rate out of the unit, so it is not explicitly considered in the surface impoundment flow model.

- **Effective hydraulic conductivity of the clogged native material.** As liquids infiltrate soil underlying the impoundment, suspended particulate matter accumulates in the soil pore spaces, reducing hydraulic conductivity and lowering infiltration rates.

- **Effective hydraulic conductivity and thickness of a clay liner.** When the surface impoundment is underlain by a compacted clay liner, the rate of infiltration is also determined by simulating flow through a three-layer system, substituting the characteristics of the clay liner for those of the clogged soil layer.

- **Leak rate of a composite liner.** For cases where the surface impoundment is underlain by a composite liner (a geomembrane underlain by a low permeability liner such as a compacted clay liner or a geosynthetic clay liner), the surface impoundment source-term model uses a modified equation of Bonaparte et al. (1989) to calculate the infiltration rate. The equation uses, among other inputs, the head generated by the water and unconsolidated sediments in the unit, a leak density selected from an empirical distribution derived from a TetraTech (2001) study of liner leakage, a uniform leak size of 6 mm^2, and an assumed hydraulic conductivity of $1x10^{-7}$ cm/sec for the 3 feet of underlying compacted clay material.

- **Limitations on maximum infiltration rate from mounding.** If the calculated infiltration rate exceeds the rate at which the saturated zone can transport the groundwater, the groundwater level will rise into the unsaturated zone. The model accounts for groundwater mounding when calculating the infiltration rate from the surface impoundment unit and, if necessary, constrains the value to ensure that the groundwater mound does not rise to the bottom of the surface impoundment unit.

3.3.3 Surface Impoundment Model Input Parameters

Input parameters required by the surface impoundment source-term model are discussed below. Additional details on how data for these inputs were collected for the CCW risk assessment are provided in Appendix A for waste concentrations and Appendix B for surface impoundment dimensions and characteristics.

- **Surface Impoundment Area.** The model uses surface impoundment area to determine the area over which infiltration occurs. CCW surface impoundment area data were obtained from the EPRI comanagement survey (EPRI, 1997). The impoundment was assumed to be square.

- **Areal Infiltration Rate.** The surface impoundment leachate infiltration rate (or flux) is computed internally by the surface impoundment source-term model, as described in Section 3.3.2.

- **Depth Below Grade.** The depth of the bottom of the impoundment below the surrounding ground surface is used, along with depth to groundwater, to determine the thickness of the unsaturated zone beneath the impoundment. For CCW impoundments, depth below grade was sampled from an empirical distribution based on available measurements from a number of CCW surface impoundments (see Appendix B).

- **Operating Depth.** The operating (or ponding) depth is the long-term average depth of wastewater and sediment in the impoundment, measured from the base of the impoundment. For CCW surface impoundments, depth was estimated by dividing impoundment capacity by impoundment area. CCW impoundment capacity data were taken from the EPRI comanagement survey (EPRI, 1997).

- **Total Thickness of Sediment.** By default, EPACMTP models unlined surface impoundments with a layer of "sludge" or sediment above the base of the unit. The sediment layer is divided into two sublayers: an upper, loose sediment sublayer and a lower, consolidated sediment sublayer. The consolidated sediment has a relatively low hydraulic conductivity and acts to impede flow. The calculated infiltration rate is inversely related to the thickness of the consolidated sediment sublayer. A thinner consolidated sediment layer will result in a higher infiltration rate and a greater rate of constituent loss from the impoundment. The surface impoundment source-term model uses the total sediment thickness as an input parameter and assumes that it consists of equal thicknesses of loose and consolidated material. Because data were not available on CCW sediment layer thicknesses, the CCW risk assessment used the Tier 1 IWEM model assumption: a total (unconsolidated plus consolidated) sediment layer thickness of 0.2 meters (U.S. EPA, 2002b). It is not known how representative this assumption is with respect to unlined CCW surface impoundments, but it is reasonable to assume that a sediment layer would accumulate and restrict flow from the bottom of a CCW impoundment.

- **Distance to the Nearest Surface Water Body.** The distance to the nearest waterbody is used to determine the location of a fully penetrating surface waterbody at which groundwater mass and water fluxes will be calculated and reported. The distance to the nearest surface waterbody is also used as a surrogate for the distance to the nearest point at which the water table elevation is kept at a fixed value. That distance is used to calculate the estimated height of groundwater mounding underneath the impoundment to ensure that excessively high infiltration rates, which may be calculated for deep, unlined impoundments, do not occur. If necessary, the model reduces the infiltration rate to ensure the predicted water table does not rise above the ground surface. For the CCW sites, distance to surface water was sampled from an empirical distribution developed from aerial photo measurements at 59 coal-fired power plants with onsite landfills or surface impoundments (Appendix C).

- **Leachate Concentration.** The annual average leachate concentration is modeled as a constant concentration pulse with a defined duration. For a particular model run, the leachate concentration was assumed to be constant during the operation of the unit; there is no reduction in leachate concentration until the impoundment ceases operation. Leachate concentrations for CCW impoundments were obtained by waste type from surface impoundment porewater data from EPA's CCW Constituent Database, as described in Appendix A.

- **Source Leaching Duration.** For surface impoundments, the addition and removal of waste during the operational life period are more or less balanced, without significant net accumulation of waste. In the finite-source implementation used for CCW surface impoundments, the duration of the leaching period is assumed to be the same as the operational life of the surface impoundment. Based on industry data (see Appendix B) for CCW surface impoundments, we used a high-end (90th percentile) fixed surface impoundment operating life of 75 years. A high-end value was appropriate because CCW surface impoundments are typically closed with waste in place, while the surface impoundment source-term model assumes clean closure (waste removed). In addition, operating life is not a particularly sensitive parameter in this analysis: the difference between the 50th percentile value (40 years) and the 90th percentile value used (75 years) is less than a factor of two.

- **Liner Type, Thickness, Hydraulic Conductivity, and Leak Density.** The type of liner is used to calculate leachate flux from the impoundment. To assign one of the three liner scenarios to each facility in the EPRI survey (EPRI, 1997), we used the same crosswalk as we used for landfills (see Table 3-2). Attachment B-2 to Appendix B provides these assignments, along with the original EPRI liner type, for each CCW surface impoundment modeled.

As with IWEM (U.S. EPA, 2002b), clay liners were assumed to be 3 feet thick and to have a constant hydraulic conductivity of 10^{-7} cm/s, reflecting typical design specifications for clay liners. For composite liners, infiltration was assumed to result from defects (pin holes) in the geomembrane. The pin holes were assumed to be circular and uniformly sized (6 mm^2). The leak density was defined as the average number of circular pin holes per square meter and was obtained from a study of industrial surface impoundment membrane liner leak rates by Tetra Tech (2001).

3.3.4 Surface Impoundment Model Outputs

For each year in the simulation, the surface impoundment source-term model uses the average annual leachate concentration and calculates an infiltration rate to estimate the constituent flux through the bottom of the impoundment. This time series is used as an input for the EPACMTP unsaturated zone model.

3.4 Groundwater Model

This section describes the methodology and the models that were used to predict the fate and transport of chemical constituents in soil and groundwater to determine impacts on drinking

water wells and surface water that is connected to groundwater. The surface water model used to address the groundwater-to-surface water pathways is described in Section 3.5.

3.4.1 Conceptual Model

The groundwater pathway was modeled to determine the receptor well concentrations and contaminant flux to surface water resulting from the release of waste constituents from a WMU. The release of a constituent occurs when liquid percolating through the WMU becomes leachate as it infiltrates from the bottom of the WMU into the subsurface. For landfills, the liquid percolating through the landfill is from water in the waste and precipitation. For surface impoundments, the percolating liquid is primarily the wastewater managed in the impoundments.

Waste constituents dissolved in the leachate are transported through the unsaturated zone (the soil layer under the WMU) to the underlying saturated zone (i.e., groundwater). Once in the groundwater, contaminants are transported downgradient to a hypothetical receptor well or waterbody. For this analysis, the groundwater concentration was evaluated for three receptor locations, each at a specified distance from the downgradient edge of the WMU:

- The intake point of a hypothetical residential drinking water well (the receptor well), which is used for the residential drinking water pathway
- A nearby river, stream, or lake, which is modeled as a fully penetrating surface waterbody and is used for the fish ingestion and ecological pathways.

Figure 3-6 shows the conceptual model of the groundwater fate and transport of contaminant releases from a WMU to a downgradient receptor well.

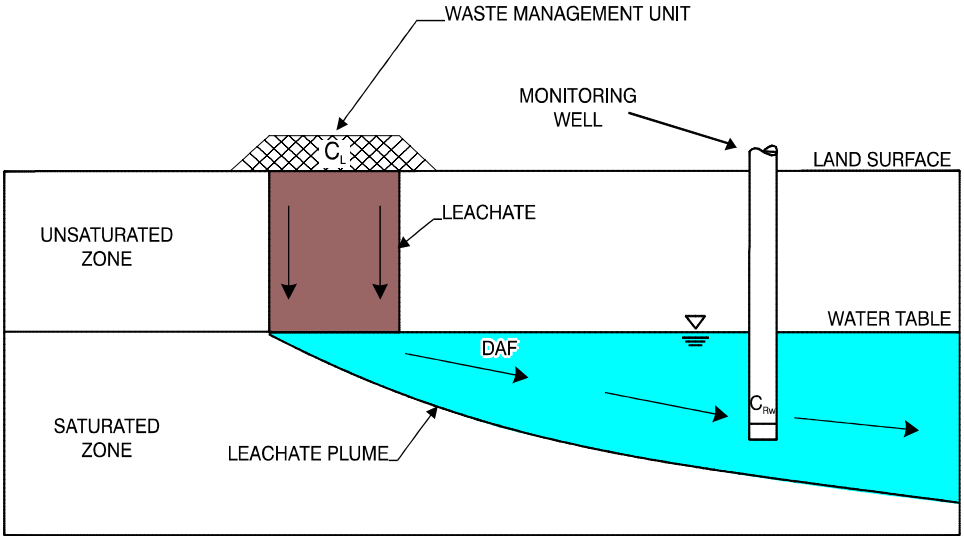


Figure 3-6. Conceptual model of the groundwater modeling scenario.

3.4.2 Modeling Approach and Assumptions

The transport of leachate from the WMU through the unsaturated and saturated zones was modeled using EPACMTP (U.S. EPA, 1996, 1997a, 2003a, 2003d, 2003d). EPACMTP is a

composite model consisting of two coupled modules: (1) a one-dimensional module that simulates infiltration and dissolved contaminant transport through unsaturated soils, and (2) a 3-dimensional saturated zone flow and transport module to model groundwater fate and transport. EPACMTP has been used by EPA to make regulatory decisions for wastes managed in land disposal units (including landfills and surface impoundments) for a number of solid waste and hazardous waste regulatory efforts, and as noted earlier, has undergone extensive peer review. EPACMTP simulates the concentration arriving at a specified receptor location (such as a well or stream).

The primary subsurface transport mechanisms modeled by EPACMTP are (1) downward (1-dimensional) movement along with infiltrating water flow in the unsaturated zone soils and (2) movement and dispersion along with ambient groundwater flow in the saturated zone. EPACMTP models soils and aquifer as uniform porous media and does not account for preferential pathways such as fractures and macropores or for facilitated transport, which may affect migration of strongly sorbing constituents such as metals.

In the unsaturated zone, flow is gravity driven and prevails in the downward direction. Therefore, the flow is modeled in the unsaturated zone as one-dimensional in the vertical direction. The model also assumes that transverse (sideways) dispersion (from both mechanical and molecular diffusion processes) is negligible in the unsaturated zone because the scale of lateral migration due to transverse dispersion is negligible compared with the size of the WMUs. This assumption is also environmentally protective because it allows the leading front of the contaminant plume to arrive at the water table with greater peak concentration in the case of a finite source.

In the saturated zone, the EPACMTP model assumes that movement of chemicals is driven primarily by ambient groundwater flow, which in turn is controlled by a regional hydraulic gradient and hydraulic conductivity in the aquifer formation. The model does take into account the effects of infiltration through the WMU, as well as regional recharge into the aquifer around the WMU. Infiltration through the WMU increases the groundwater flow in all directions under and near the WMU and may result in groundwater mounding. This 3-dimensional flow pattern enhances the horizontal and vertical spreading of the contaminant plume. The effect of recharge (outside the WMU) is to cause a downward (vertical) movement of the contaminant plume as it travels along groundwater flow direction. In addition to advective movement with the groundwater flow, the model simulates mixing of contaminants with groundwater due to hydrodynamic dispersion, which acts along the groundwater flow direction, as well as vertically and in the horizontal transverse direction.

To model sorption of CCW constituents in the unsaturated zone, soil-water partitioning coefficients (K_d values) for metal constituents were selected from nonlinear sorption isotherms generated from the equilibrium geochemical speciation model MINTEQA2 (U.S. EPA, 2001a). Chemicals with low K_d values will have low retardation factors, which means that they will move at nearly the same velocity as the groundwater. Chemicals with high K_d values will have high retardation factors and may move many times slower than groundwater. As described in Appendix D, CCW-specific partition coefficients were developed with MINTEQA2 considering

CCW leachate chemistry, including the highly alkaline chemistries that are characteristic of some CCWs.

MINTEQA2 is a product of ORD, and like EPACMTP, has a long history of peer- and SAB-review during its development, use, and continued improvement for regulatory support over the past two decades. These reviews largely focused on the use of MINTEQA2 to generate sorption isotherms for metals for EPACMTP, which is how it was used in the CCW risk assessment. Two of the more recent peer reviews include one for application within the 3MRA model (U.S. EPA, 1999d) and a review of its use and application to RCRA rulemaking and guidance support, including revisions made to the model to support IWEM and the CCW rulemaking efforts (U.S. EPA, 2003f). In the latter review, three experts found that the revisions made to the MINTEQA2 model were appropriate, but also suggested further improvements in how the model addresses environments with highly alkaline leachate (such as CCW sites). As explained in Appendix D, these comments were addressed in this application of MINTEQA2 to CCW waste transport by the development of sorption isotherms that are specific to geochemical conditions encountered in CCW landfills and surface impoundments.

3.4.3 Model Inputs and Receptor Locations

EPACMTP requires information about soil and aquifer properties as model inputs. For soils, EPACMTP uses soil texture to generate consistent hydrological properties for the unsaturated zone model, and soil pH and organic matter to select appropriate sorption coefficients to model contaminant sorption in the soil. As described in Appendix C, site-specific soil texture, pH, and organic carbon data were collected around each site from the STATSGO soils database. Similarly, the hydrogeological setting around each WMU was used to select appropriate aquifer conditions from EPACMTP's Hydrogeologic Database (HGDB; see Appendix C).

Recharge is water percolating through the soil to the aquifer outside the footprint of the WMU. The recharge rate is determined by precipitation and soil texture. For the CCW landfills and surface impoundments, recharge rates were selected by soil texture and meteorological station assignment from a database of HELP model–derived recharge rates for climate stations across the country that is included in the EPACMTP input files. Further details about how these rates were determined and other options for determining recharge rates outside of the EPACMTP model can be found in the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2003a).

One of the most important inputs for EPACMTP is receptor location, which for this risk assessment includes residential drinking water wells and surface water bodies. Figure 3-7 shows a schematic of how residential well drinking water intakes were defined in terms of their radial downgradient distance from the WMU and the angle off the contaminant plume centerline. The shaded areas in Figure 3-7 represent the horizontal extent of the contaminant plume.

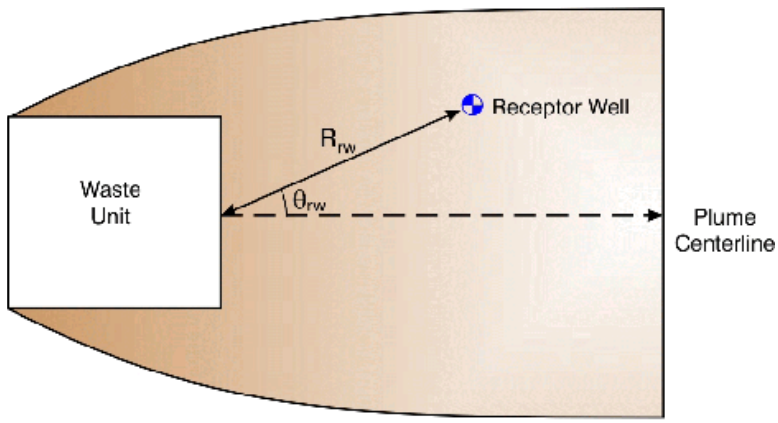


Figure 3-7. Schematic plan view showing contaminant plume and receptor well location.

In this analysis, receptor wells were located randomly within the contaminant plume, as follows:

- Because residential well distance data are not available for CCW WMUs, EPA based the radial downgradient distance on a nationwide distribution of the nearest downgradient residential or municipal wells from a survey of Subtitle D municipal solid waste landfills (U.S. EPA, 1988a; see Appendix C). The maximum radial distance in this survey was 1 mile. EPA believes that this distribution is protective of CCW WMUs, but because information on the actual distance of drinking water wells from CCW facilities is very limited, EPA is seeking comments and additional data that are relevant to this issue.

- The angle off the contaminant plume centerline (θ_{rw} in Figure 3-7) was based on a uniform distribution ranging from zero to ninety degrees.

- Wells were placed within the lateral extent of the contaminant plume (shaded portion in Figure 3-7).

- The depth of the well intake point was based on a uniform distribution with limits of 0 (i.e., well at the water table) to 10 meters (or the total saturated aquifer thickness if the aquifer is less than 10 meters thick).

The location of the surface waterbody intercepting groundwater flow was specified for each flow and transport simulation. The waterbody was constrained to lie across the contaminant plume centerline and its depth was varied uniformly throughout the aquifer thickness or throughout the upper 10 m of the aquifer thickness, whichever was less.

Downgradient distance to the surface waterbody was determined from an empirical distribution of distances measured for CCW landfills and surface impoundments (see Appendix C), which was randomly sampled to develop the distances used in EPACMTP to calculate groundwater concentrations at those distances in the Monte Carlo analysis.

3.4.4 Groundwater Model Outputs

The output of EPACMTP is a prediction of the contaminant concentration arriving at a downgradient groundwater receptor location (either a well or a surface water body). Because a finite-source scenario was used, the concentration is time-dependent. A maximum time-averaged concentration was calculated for each constituent across the exposure duration selected in each Monte Carlo iteration.

3.5 Surface Water Models

For the groundwater-to-surface-water pathway, chemical contaminants leach out of WMUs and into groundwater, and this contaminated groundwater then discharges into a surface waterbody through groundwater discharge. Once in the waterbody, the continued fate and transport of the contaminants is modeled with a surface water model, which uniformly mixes the contaminants in a single stream segment. Surface water flows in and out of the stream segment. Surface water flowing into the stream segment is assumed to have zero constituent concentration, and surface water flowing out has nonzero constituent concentrations due to the groundwater contamination. EPACMTP assumes a fully penetrating stream; therefore, the entire groundwater and contaminant flux is passed to the surface water model. To ensure that an unrealistic flux of contaminated groundwater does not occur, the groundwater flow into the waterbody is compared to the stream flow. If the groundwater flux exceeds the stream flow, it is capped at the stream flow and the contaminant flux is reduced using the ratio of the stream flow to the incoming groundwater flow (i.e., all of the stream flow is assumed to be from groundwater discharge and the total concentration in the stream is equal to the groundwater concentration).

The waterbody considered in the CCW risk assessment is a river, stream, or lake located downgradient of the WMU. As described in Appendix C, the flow characteristics and dimensions for this waterbody are determined by site-specific stream flow data, the width of the groundwater contaminant plume as it intersects the waterbody, and established relationships between flow and stream depth. The stream segment modeled in this assessment is assumed to be homogeneously mixed.

Simple equilibrium partitioning models were used to estimate contaminant concentrations in the water column, suspended and bed sediments (see Section 3.5.1), and aquatic organisms (see Section 3.5.2). Special modeling provisions for aluminum are described in Section 3.5.3.

3.5.1 Equilibrium Partitioning Model

The primary surface water model used to estimate groundwater impacts on waterbodies is a simple steady-state equilibrium-partitioning model adapted from models in EPA's Indirect Exposure Methodology (IEM; U.S. EPA, 1998c) and Human Health Risk Assessment Protocol (HHRAP; U.S. EPA, 1998d). This model is based on the concept that dissolved and sorbed concentrations can be related through equilibrium partitioning coefficients. This model was used for all constituents except aluminum, which was modeled based on a solubility approach (see Section 3.5.3). Although these models have not been specifically peer reviewed in this application, they have been subject to the Agency's peer review process as part of the development of the IEM and HHRAP.

The model partitions the total mass of chemical contaminant in the waterbody into four compartments:

- Constituents dissolved in the water column
- Constituents sorbed onto suspended solids
- Constituents sorbed onto sediment particles at the bottom of the waterbody
- Constituents dissolved in porewater in the sediment layer.

Table 3-4 provides the partitioning coefficients used by the surface water model to estimate contaminant partitioning between water and suspended solids in the water column and between sediment and porewater in the sediment layer. These distributions were derived from published empirical data as described in U.S. EPA (1999b).

Table 3-4. Sediment/Water Partition Coefficients: Empirical Distributions[a]

Chemical	Distribution Type	Minimum	Mean	Maximum	SD
Aluminum	not used				
Antimony	log normal	0.6	3.6	4.8	1.8
Arsenic	log normal	1.6	2.4	4.3	0.7
Barium	log normal	0.9	2.5	3.2	0.8
Boron	log normal	-0.5	0.8	1.4	0.5
Cadmium	log normal	0.5	3.3	7.3	1.8
Cobalt	log normal	2.2	3.9	5.3	0.8
Lead	log normal	2.0	4.6	7.0	1.9
Molybdenum	log normal	1.3	2.2	3.2	0.9
Selenium IV	log normal	1.0	3.6	4.0	1.2
Selenium VI	log normal	-1.4	0.6	3.0	1.2
Thallium	log normal	-0.5	1.3	3.5	1.1
Total Nitrate Nitrogen	constant	0	0	0	0

Source: U.S. EPA (1999b).
SD = standard deviation.
[a] All values are log values.

Following calculation of the constituent loading and loss rates, the surface water model estimates steady-state, equilibrium waterbody contaminant concentrations in each compartment using equations presented in Attachment E-1 to Appendix E. For evaluating risks to human health from fish consumption, the model calculates waterbody concentrations using groundwater loadings that are explicitly averaged over the exposure period for the each human receptor (i.e., adult and child fishers). These average waterbody concentrations are then used to calculate fish concentrations as described in Section 3.5.2. Ecological risks were based on waterbody concentrations calculated using the peak annual groundwater loading value from EPACMTP.

The equilibrium–partitioning model, as implemented, is conservative because there are no loss mechanisms (e.g., burial) for any of the constituents.

3.5.2 Aquatic Food Web Model

An aquatic food web model was used to estimate the concentration of CCW constituents that accumulate in fish. This risk assessment assumes that fish are a food source for a recreational fisher. Trophic level three (TL3) and four (TL4) fish[6] were considered in this analysis because most of the fish that humans eat are T4 fish (e.g., salmon, trout, walleye, bass) and medium to large T3 fish (e.g., carp, smelt, perch, catfish, sucker, bullhead, sauger). The aquatic food web model has been peer reviewed as part of the 3MRA model development effort (see http://www.epa.gov/ epaoswer/hazwaste/id/hwirwste/peer03/aquatic/aqtfooda.pdf).

The aquatic food web model calculates the concentration in fish from the concentration calculated for the waterbody downgradient from the CCW disposal site. The contaminants in the water column consist of dissolved constituents and constituents sorbed to suspended solids. For all constituents, the contaminant concentrations in fish were calculated from the total waterbody concentration (i.e., dissolved plus sorbed to suspended solids) using bioconcentration factors (BCFs), which are presented in Table 3-5. The equations used to model fish tissue concentrations are provided in Attachment E-2 to Appendix E.

Table 3-5. Bioconcentration Factors for Fish

CAS	Chemical	T3 Value	T4 Value	Units	Reference
7429-90-5	Aluminum	ND	ND	L/kg	
7440-36-0	Antimony	0	0	L/kg	Barrows et al. (1980)
22569-72-8	Arsenic (III)	4.0E+00	4.0E+00	L/kg	Barrows et al. (1980)
15584-04-0	Arsenic (V)	4.0E+00	4.0E+00	L/kg	Barrows et al. (1980)
7440-39-3	Barium	ND	ND	L/kg	
7440-42-8	Boron	ND	ND	L/kg	
7440-43-9	Cadmium	2.7E+02	2.7E+02	L/kg	Kumada et al. (1972)
7440-48-4	Cobalt	ND	ND	L/kg	
7439-92-1	Lead	4.6E+01	4.6E+01	L/kg	Stephan (1993)
7439-98-7	Molybdenum	4.0E+00	4.0E+00	L/kg	Eisler (1989)
10026-03-6	Selenium (IV)	4.9E+02	1.7E+03	L/kg	Lemly (1985)
7782-49-2	Selenium (VI)	4.9E+02	1.7E+03	L/kg	Lemly (1985)
7440-28-0	Thallium	3.4E+01	1.3E+02	L/kg	T3: Barrows et al. (1980) T4: Stephan (1993)
14797-55-8	Total Nitrate Nitrogen	ND	ND	L/kg	

ND = No Data. Fish concentrations were not calculated for constituents with no BCF data.

[6] TL3 fish are those that consume invertebrates and plankton; TL4 fish are those that consume other fish.

3.5.3 Aluminum Precipitation Model

A simple precipitation model was used for aluminum in lieu of the equilibrium-partitioning model, because aluminum is generally solubility limited in natural waters. The MINTEQA2 model was used to estimate total soluble aluminum concentrations as a function of pH for a typical surface waterbody (Stumm and Morgan, 1996; Drever, 1988). By assuming the common aluminum silicate mineral gibbsite was the equilibrium solid phase, the computed values of total dissolved aluminum were interpreted as the maximum expected for each pH. If more aluminum were added to the system, it would be expected to precipitate as the mineral gibbsite for the system to maintain equilibrium. Table 3-6 shows the maximum dissolved aluminum concentrations as a function of waterbody pH.

The precipitation model initially calculates the aluminum concentration in the surface water column by assuming that all aluminum in the groundwater flux is dissolved. If this concentration exceeds the maximum soluble concentration based on pH, the dissolved concentration is capped and the excess aluminum is assumed to precipitate as the mineral gibbsite and settle to the benthic sediment layer. The equations used in this model are presented in Appendix E.

Table 3-6. Aluminum Solubility as a Function of Waterbody pH[a]

Minimum pH	Maximum pH	Solubility (mg/L)
3.5	4.5	26.2
4.5	5	1.84
5	5.5	0.196
5.5	6	0.0112
6	6.5	0.00143
6.5	7	0.000662
7	7.5	0.000915
7.5	8	0.00229
8	8.5	0.00682
8.5	9	0.0212
9	9.5	0.0666
9.5	10	0.211
10	10.5	0.668

[a] Computed using MINTEQA2

Only the water column concentration for aluminum was used in subsequent exposure and risk calculations, because there is no available ecological benchmark for aluminum in sediment. The water column concentration was used to calculate human exposure via drinking water ingestion, as well as risk to ecological receptors exposed via direct contact.

3.6 Human Exposure Assessment

The human exposure component of the full-scale analysis assessed the magnitude, frequency, duration, and route of exposure to CCW contaminants that an individual may experience. The term "exposure," as defined by the EPA exposure guidelines (U.S. EPA, 1992), as the condition that occurs when a contaminant comes into contact with the outer boundary of the body. The exposure of an individual to a contaminant completes an exposure pathway (i.e., the course a constituent takes from the WMU to an exposed individual). Once the body is exposed, the constituent can cross the outer boundary and enter the body. The amount of contaminant that crosses and is available for adsorption at internal exchange boundaries is referred to as the "dose" (U.S. EPA, 1992).

This risk assessment evaluated the risk from CCW contaminants to receptors in the vicinity of a WMU. The individuals evaluated were those residents closest to the WMU. The distances from the WMU to the residents were taken from a distribution of distances to the nearest residential drinking water well measured for municipal landfills and, for the recreational fisher, a distribution of the distance of the nearest surface water body from CCW landfills and surface impoundments (see Appendix C).

Section 3.6.1 presents an overview of the receptors and selected exposure pathways considered for this assessment, including a discussion of how childhood exposure is considered in the analysis. Section 3.6.2 presents exposure factors (i.e., values needed to calculate human exposure) used in the analysis. Section 3.6.3 describes the methods used to estimate dose, including average daily dose (ADD) and lifetime average daily dose (LADD).

3.6.1 Receptors and Exposure Pathways

Human receptors may come into contact with constituents present in environmental media through a variety of pathways. The exposure pathways considered in the full-scale analysis were ingestion of drinking water from contaminated groundwater sources and ingestion of fish from surface water contaminated by groundwater.

- **Ingestion of Drinking Water.** Groundwater from an offsite well was assumed to be used for drinking water for residents (adult and child).
- **Ingestion of Fish.** Fish are exposed to constituents via uptake of contaminants from surface water. Adult recreational fishers and their children were assumed to consume fish caught in local waterbodies. Although conservative, EPA considers this assumption to be reasonable and protective for fishers relying on locally caught fish as a food source.

Table 3-7 lists each human receptor type considered in this analysis along with the specific exposure pathways that apply to that receptor. Both adult and child residents are exposed by drinking groundwater, and adult fishers and their children are exposed by eating fish caught in streams and lakes impacted by CCW.

Table 3-7. Receptors and Exposure Pathways

Receptor	Ingestion of Drinking Water	Ingestion of Fish
Adult resident	✓	
Child resident	✓	
Adult recreational fisher		✓
Child of recreational fisher		✓

Childhood Exposure

Children are an important subpopulation to consider in a risk assessment because they may be more sensitive to exposures than adults. Compared with adults, children may eat more food and drink more fluids per unit of body weight. This higher intake-rate-to-body-weight ratio can result in a higher ADD for children than adults.

As children mature, their physical characteristics and behavior patterns change. To capture these changes in the analysis, the life of a child was considered in stages represented by the following cohorts: cohort 1 (ages 1 to 5), cohort 2 (ages 6 to 11), cohort 3 (ages 12 to 19), and cohort 4 (ages 20 to 70). Associated with each cohort are distributions of exposure parameters that reflect the physical characteristics and behavior patterns of that age range. These exposure parameters are required to calculate exposure to an individual. The distributions for the 20- to 70-year-old cohort were the same as those used for adult receptors.

To capture the higher intake-rate-to-body-weight ratio of children, a start age of 1 year was selected for the child receptors. The exposure duration distribution for cohort 1 (a 1- to 5-year-old) was used to define exposure duration for the child receptors for each of the 10,000 iterations in the probabilistic analysis. For each individual iteration, the child receptor is aged through the age cohorts as appropriate until the age corresponding to the selected exposure duration is reached (e.g., if an exposure duration of 25 years was selected for an iteration, the child was aged from 1 year to 25 years, spending 5 years in cohort 1, 6 years in cohort 2, 8 years in cohort 3, and 6 years in cohort 4, for a total of 25 years).

3.6.2 Exposure Factors

The exposure factors used are listed in Table 3-8, along with their data sources and variable type (i.e., whether they were represented as a distribution or a fixed value in the Monte Carlo analysis). These exposure factors were used to calculate the dose of a chemical based on contact with contaminated media or food, the duration of that contact, and the body weight of the exposed individuals.

Table 3-8. Human Exposure Factor Input Parameters and Data Sources

Parameter	Variable Type	Data Source
Body weight (adult, child)	Distribution	U.S. EPA (1997c)
Ingestion rate: fish (adult, child)	Distribution	U.S. EPA (1997d)
Ingestion rate: drinking water (adult, child)	Distribution	U.S. EPA (1997c)
Exposure duration (adult, child)	Distribution	U.S. EPA (1997e)
Exposure frequency (adult, child)	Fixed (constant)	U.S. EPA policy
Fraction contaminated: drinking water	Fixed (constant)	U.S. EPA policy
Fraction contaminated: fish	Fixed (constant)	U.S. EPA policy
Fraction of TL3 fish consumed	Fixed (constant)	U.S. EPA (1997d)
Fraction of TL4 fish consumed	Fixed (constant)	U.S. EPA (1997d)
Human lifetime (used in carcinogenic risk calculation)	Fixed (constant)	U.S. EPA policy

The primary data source of human exposure model inputs used in this risk assessment was EPA's *Exposure Factors Handbook* (EFH; U.S. EPA, 1997c-e). The EFH summarizes data on human behaviors and characteristics related to human exposure from relevant key studies and provides recommendations and associated confidence estimates on the values of exposure factors. These data were carefully reviewed and evaluated for quality before being included in the EFH. EPA's evaluation criteria included peer review, reproducibility, pertinence to the United States, currency, adequacy of the data collection period, validity of the approach, representativeness of the population, characterization of variability, lack of bias in study design, and measurement error (U.S. EPA, 1997c-e). For exposure factors that were varied in the Monte Carlo analysis, probability distribution functions were developed from the values in the EFH.

The data sources and assumptions for intake and other human exposure factors used in this analysis are described below. Appendix F presents the exposure factors used and describes the rationale and data used to select the form of the distributions (e.g., normal, lognormal, gamma, Weibull) for those exposure factors that were varied in the probabilistic analysis.

- **Body Weight.** Distributions of body weight were developed for adult and child receptors based on data from the EFH.

- **Fish Ingestion Rate.** Fish ingestion rates were based on a recreational angler who catches and eats some fish from a waterbody impacted by contaminants released from CCW WMUs. Distributions of fish intake rates were developed for adult fishers based on data from the EFH. Because the EFH does not have fish ingestion rates for children, adult ingestion rates were used (as a conservative assumption).

- **Drinking Water Ingestion Rate.** Distributions of drinking water intake rates were developed for the adult and child resident based on data from the EFH.

- **Exposure Duration.** Exposure duration refers to the amount of time that a receptor is exposed to a contaminant source. Exposure duration was assumed to correspond with the receptor's residence time in the same house. Exposure durations were determined using data on residential occupancy from the EFH. The data used to develop

parameter information for resident receptors were age-specific. Thus, separate exposure duration distributions were developed for adult and child residents.

- **Exposure Frequency.** Exposure frequency is the frequency with which the receptor is exposed to the contaminated source during the exposure duration. Exposure frequency is not expected to vary much, so distributions were not developed for exposure frequency. All receptors were assumed to be exposed to the contaminant source 350 days/year. This value is based on the conservative assumption that individuals are away from their homes (e.g., on vacation) approximately 2 weeks out of the year, but are otherwise exposed daily.

- **Lifetime and Averaging Time.** Averaging time is the period of time over which a receptor's dose is averaged. To evaluate carcinogens, total dose was averaged over the lifetime of the individual, assumed to be 70 years. To evaluate noncarcinogens, dose was averaged over the last year of exposure because noncancer effects may become evident during less-than-lifetime exposure durations if toxic thresholds are exceeded. Essentially, this amounts to setting exposure duration and averaging time equal so that they cancel each other out in the equation for ADD. Thus, neither exposure duration nor averaging time is included in the ADD equation.

3.6.3 Dose Estimates

An exposure assessment estimates the dose to each receptor from the contaminant concentration in the exposure medium (e.g., drinking water, fish) and the intake rate for that medium (e.g., ingestion rate of drinking water, ingestion rate of fish). For this assessment, exposure estimates were based on the *potential* dose (e.g., the dose ingested) rather than the applied dose (e.g., the dose delivered to the gastrointestinal tract) or the internal dose (e.g., the dose delivered to the target organ). Doses from groundwater or fish ingestion were calculated by multiplying the contaminant concentration in groundwater or fish by the respective intake rate on a per kilogram body weight basis. Doses were then summed over the exposure duration, resulting in an ADD received from ingestion exposure. The ADD was used to assess noncancer risk from ingestion exposures and is defined as

$$ADD = C \times IR \tag{3-2}$$

where

C = average concentration (mass/volume or mass/mass)
IR = intake rate (mass/body weight mass/time, or volume/body weight mass/time).

Contaminant concentration represents the concentration of a chemical in a medium that contacts the body. The ADD was calculated from concentrations averaged over the exposure duration for each receptor.

For cancer effects, where the biological response is described in terms of lifetime probabilities even though exposure may not occur over the entire lifetime, dose is presented as a

LADD. The LADD was used to assess cancer risks from each exposure route (i.e., ingestion) and is defined as

$$LADD = \frac{C \times IR \times ED \times EF}{AT \times 365} \tag{3-3}$$

where

C	=	average concentration (mass/mass or mass/volume)
IR	=	intake rate (mass/body weight mass/time, or volume/body weight mass/time)
ED	=	exposure duration (yr)
EF	=	exposure frequency (d/yr)
AT	=	averaging time (yr)
365	=	units conversion factor (d/yr).

As with the ADD, contaminant concentration represents the concentration of a chemical in a medium that contacts the body. Intake rate depends on the route of exposure; for example, it might be an inhalation rate or an ingestion rate. Exposure frequency is the number of days per year the receptor is exposed to the contaminated source during the exposure duration.

For cancer effects, biological responses are described in terms of lifetime probabilities, even though exposure may not be lifelong; consequently, the exposure duration (the length of time of contact with a contaminant) was used to average the ADD over a lifetime (70 years). The media concentrations used were averaged over the duration of exposure.

3.7 Toxicity Assessment

A chemical's ability to cause an adverse human health effect depends on the toxicity of the chemical, the chemical's route of exposure to an individual (ingestion, inhalation, or direct contact), the duration of exposure, and the dose received (the amount that a human ingests or inhales). Similar principles apply to ecological receptors, although exposure duration is much shorter than for human receptors because humans generally live longer then ecological receptors. For a risk assessment, the toxicity of a constituent is defined by a human health or ecological benchmark for each route of exposure. A benchmark is a quantitative value used to predict a chemical's possible toxicity and ability to induce an adverse effect at certain levels of exposure. Because different chemicals cause different health effects at different doses, benchmarks are chemical-specific.

Appropriate human health and ecological benchmarks for the constituents of potential concern in CCW wastes were collected as part of the screening assessment. The same benchmarks were used in the full-scale risk assessment, with a few updates. The data sources and collection methodology for these benchmarks are described briefly in Sections 3.7.1 (human health benchmarks) and 3.7.2 (ecological benchmarks), and in more detail in Appendix G (human health benchmarks) and Appendix H (ecological benchmarks). The discussion here is limited to the 12 constituents assessed in the full-scale risk assessment and for humans, covers

only oral benchmarks (because all inhalation pathway risks fell below the screening criteria in the screening assessment). Appendices G and H cover all constituents and routes.

3.7.1 Human Health Benchmarks

Human health benchmarks for chronic oral exposures were needed for the full-scale analysis. These health benchmarks were derived from toxicity data based on animal studies or human epidemiological studies. Each benchmark represents a dose-response estimate that relates the likelihood and severity of adverse health effects to exposure and dose. This section presents the noncancer and cancer benchmarks used to evaluate human health effects that may result from exposure to the constituents modeled.

Chronic human health benchmarks were used to evaluate potential noncancer and cancer risks. These include reference doses (RfDs) to evaluate noncancer risk from oral exposures and oral cancer slope factors (CSFs) to evaluate cancer risk from oral exposures. The benchmarks are chemical-specific and do not vary between age groups.

- The **RfD** is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious noncancer effects during a lifetime. The RfD provides a reference point to gauge the potential effects (U.S. EPA, 2002c). At exposures increasingly greater than the RfD, the potential for adverse health effects increases. Lifetime exposure above the RfD does not imply that an adverse health effect would necessarily occur.

- The **CSF** is an upper-bound estimate (approximating a 95 percent confidence limit) of the increased human cancer risk from a lifetime exposure to an agent. This estimate is usually expressed in units of proportion (of a population) affected per milligram of agent per kilogram body weight per day (mg/kg-d). Unlike RfDs, CSFs do not represent “safe” exposure levels; rather, they relate levels of exposure with a probability of effect or risk.

Human health benchmarks are available from several sources. Health benchmarks developed by EPA were used whenever they were available. Sources of human health benchmarks were used in the following order of preference:

- Integrated Risk Information System (IRIS) (U.S. EPA, 2002c)
- Superfund Technical Support Center Provisional Benchmarks
- Health Effects Assessment Summary Tables (HEAST) (U.S. EPA, 1997f)
- Various other EPA health benchmark sources
- ATSDR minimal risk levels (MRLs) (ATSDR, 2002).

These sources are described in more detail in Appendix G.

The chronic human health benchmarks used in the full-scale analysis are summarized in Table 3-9. For most constituents, human health benchmarks were available from IRIS. Benchmarks for a few constituents were obtained from ATSDR and Superfund Provisional

Benchmarks U.S. EPA (2001c,d). For chemicals for which purely health-based benchmarks were not available (lead), a drinking water action level was used (U.S. EPA, 2002d).

Cadmium has two RfDs, one for exposures via water and one for exposures via food. The RfD for water was used for drinking water ingestion and the RfD for food was used for fish consumption.

Table 3-9. Human Health Benchmarks Used in the Full-Scale Analysis

Constituent	Type of Benchmark	Value	Units	Source[a]
Cancer Benchmark				
Arsenic	CSF	1.5E+00	$(mg/kg\text{-}d)^{-1}$	IRIS
Noncancer Benchmarks				
Aluminum	RfD	2.0E+00	mg/kg-d	ATSDR
Antimony	RfD	4.0E-04	mg/kg-d	IRIS
Barium	RfD	2.0E-01	mg/kg-d	IRIS
Boron	RfD	2.0E-01	mg/kg-d	IRIS
Cadmium	RfD (water)[b]	5.0E-04	mg/kg-d	IRIS
	RfD (food)[c]	1.0E-03	mg/kg-d	IRIS
Cobalt	RfD	2.0E-02	mg/kg-d	Superfund
Lead	MCL	0.015	mg/L	DWAL
Molybdenum	RfD	5.0E-03	mg/kg-d	IRIS
Nitrate/Nitrite	MCL[d]	10	mg/L	DWAL
Selenium	RfD	5.0E-03	mg/kg-d	IRIS
Thallium	RfD	8.0E-05	mg/kg-d	IRIS

[a] References:
ATSDR: Minimal Risk Levels, ATSDR (2002)
DWAL: Drinking Water Action Level, U.S. EPA (2002d)
Superfund: Superfund Risk Issue Paper, U.S. EPA (2001c,d)
IRIS: U.S. EPA (2002c)
HEAST: U.S. EPA (1997f)
[b] Used for drinking water ingestion.
[c] Used for fish ingestion.
[d] For nitrate.

3.7.2 Ecological Benchmarks

The ecological risk assessment addresses two routes of exposure for ecological receptors, direct contact with contaminated media and ingestion of contaminated food items. For each constituent for which ecological effect data were available, HQs were calculated using chemical-specific media concentrations assumed to be protective of ecological receptors of concern. To calculate ecological HQs, these media concentrations (also known as chemical stressor concentration limits [CSCLs]) were divided by the estimated media concentrations. The CSCLs are media-specific environmental quality criteria intended to represent a protective threshold value for adverse effects to various ecological receptors in aquatic ecosystems (surface water and sediment). The CSCLs were developed to be protective of the assessment endpoints chosen for this assessment. An HQ greater than 1 indicates that the predicted concentration exceeds the CSCL, and therefore, the potential for adverse ecological effects exists. In this regard, the use of

CSCLs to calculate an ecological HQ is analogous to the use of the reference concentration (RfC) for human health where the air concentration is compared to the health-based concentration (the RfC), and an HQ greater than 1 is considered to indicate the potential for adverse health effects.

Table 3-10 shows the receptor types assessed for each exposure route (direct contact and ingestion) in each environmental medium addressed by the CCW risk assessment.

Table 3-10. Ecological Receptors Assessed by Exposure Route and Medium (Surface Water or Sediment)

Receptor Type	Surface Water (water column)	Surface Water Sediment
Direct Contact Exposure		
Aquatic Community	✔	
Sediment Community		✔
Amphibians	✔	
Aquatic Plants and Algae	✔	
Terrestrial Plants		
Ingestion Exposure		
Mammals	✔	
Birds	✔	

Ecological receptors that live in close contact with contaminated media are considered to be potentially at risk. These receptors are exposed through direct contact with contaminants in surface water and sediment. The benchmarks for receptor communities (aquatic or sediment communities) are not truly *community-level* concentration limits in that they do not consider predator-prey interactions. Rather, they are based on the theory that protection of 95 percent of the species in the community will provide a sufficient level of protection for the community (see, for example, Stephan et al., 1985, for additional detail). Appendix H summarizes the benchmark derivation methods for each receptor assessed for the direct contact route of exposure.

The ingestion route of exposure addresses the exposure of terrestrial mammals and birds through ingestion of aquatic plants and prey. Thus, the benchmarks for ingestion exposure represent media concentrations that, based on certain assumptions about receptor diet and foraging behavior, are expected to be protective of populations of mammals and birds feeding and foraging in contaminated areas.

For birds and mammals, the derivation of ingestion benchmarks required the selection of appropriate ecotoxicological data based on a hierarchy of sources. The assessment endpoint chosen for birds and mammals was population viability and therefore, the ingestion benchmarks were based on study data for physiological effects that are relevant to populations. These data included measures of reproductive fitness, developmental success, survival, and other toxicological effects that could have a significant impact on the population rather than just the health of an individual animal. Choosing these measures of effect provided the basis to evaluate

the potential for adverse effects at the population level by inference; this analysis does not evaluate the effects on population dynamics in the sense that a reduction in the population is predicted over time in response to exposure to constituents released from CCW. Population-level modeling was well beyond the scope of this risk assessment.

Once an appropriate ingestion exposure study was identified, a benchmark was calculated. Appendix H describes the basic technical approach used to convert avian or mammalian benchmarks (in daily doses) to the CSCLs (in units of concentration) used to assess ecological risks for contaminated surface water and sediment. The methods reflect exposure through the ingestion of contaminated plants, prey, and various media, and include parameters on accumulation (e.g., BCFs), uptake (e.g., consumption rates), and dietary preferences.

Where multiple ecological benchmarks were available for a pathway of interest, the benchmark that produced the lowest (most sensitive) CSCL for each chemical in each medium was used. For example, several types of receptors (the aquatic community, amphibians, aquatic plants, mammals, birds) can be exposed to contaminants in surface water. The surface water criterion for a given constituent represents the lowest CSCL for these receptors, and thus gives the highest (most protective) HQ. The CSCLs used to assess ecological endpoints in the full-scale analysis and the associated receptor are summarized in Table 3-11. Additional details on the CCW ecological benchmarks and CSCLs and their development can be found in Appendix H.

Table 3-11. Ecological Risk Criteria Used in the Full-Scale Analysis

Constituent	Medium[a]	Exposure Route	CSCL	Units	Receptor
Aluminum	Surface Water	Direct contact	0.09	mg/L	Aquatic biota
Arsenic total	Sediment	Ingestion	0.51	mg/kg	Spotted sandpiper
Arsenic III	Surface Water	Direct contact	0.15	mg/L	Aquatic biota
Arsenic IV	Surface Water	Direct contact	8.10E-03	mg/L	Aquatic biota
Barium	Sediment	Ingestion	190	mg/kg	Spotted sandpiper
	Surface Water	Direct contact	4.00E-03	mg/L	Aquatic biota
Boron	Surface Water	Direct contact	1.60E-03	mg/L	Aquatic biota
Cadmium	Sediment	Direct contact	0.68	mg/kg	Sediment biota
	Surface Water	Direct contact	2.50E-03	mg/L	Aquatic biota
Cobalt	Surface Water	Direct contact	0.02	mg/L	Aquatic biota
Lead	Sediment	Ingestion	0.22	mg/kg	Spotted sandpiper
	Surface Water[b]	Ingestion	3.00E-04	mg/L	River otter
Selenium total	Surface Water	Direct contact	5.00E-03	mg/L	Aquatic biota
Selenium IV	Surface Water	Direct contact	0.03	mg/L	Aquatic biota
Selenium VI	Surface Water	Direct contact	9.5E-03	mg/L	Aquatic biota

Source: U.S. EPA (1998)
[a] If a medium (surface water or sediment) is not listed, there were insufficient data to develop a benchmark for it.
[b] Includes ingestion of fish.

Ecological benchmarks for both the screening and full-scale CCW risk assessment were taken directly from the 1998 fossil fuel combustion risk assessment, *Non-Groundwater*

Pathways, Human Health and Ecological Risk Analysis for Fossil Fuel Combustion Phase 2 (FFC2) (U.S. EPA, 1998a). The receptors and endpoints selected for the 1998 analysis were evaluated and considered appropriate for the goals of this risk assessment. The benchmarks were derived for each chemical and receptor to the extent that supporting data were available.

3.8 Risk Estimation

The final step of the risk assessment process is to estimate the risk posed to human and ecological receptors (e.g., residents, fishers; aquatic organisms). In this step, estimates of toxicity (the human health and ecological benchmarks) and exposure doses or exposure concentrations are integrated into quantitative expressions of risk. For the CCW constituents modeled in the full-scale assessment, the CCW human risk assessment uses estimates of dose and toxicity to calculate individual excess lifetime carcinogenic risk estimates and noncancer HQs (Section 3.8.1). The risk calculations for ecological receptors differ from those for humans because the ecological benchmarks are developed as media concentrations (i.e., they are calculated considering ecological exposure). Thus the CCW risk assessment uses estimates of exposure (media) concentrations and toxicity (media-specific concentration limits) to calculate an ecological HQ (Section 3.8.2).

3.8.1 Human Health Risk Estimation

The full-scale analysis focused on two human health exposure pathways: groundwater-to-drinking-water and groundwater-to-surface-water via fish consumption by recreational fishers. The cancer and noncancer health impacts of ingesting groundwater and fish contaminated by CCW leachate were estimated using the risk endpoints shown in Table 3-12. These endpoints were generated for each iteration of the Monte Carlo analysis. Only the cancer endpoint was used for arsenic, because it is the more sensitive endpoint compared to noncancer effects. For the other 11 constituents, only noncancer HQs were calculated, using the appropriate noncancer endpoint.

Table 3-12. Risk Endpoints Used for Human Health

Risk Category	Risk Endpoints	Definition
Cancer Effects (arsenic only)	Lifetime excess cancer risk by pathway and chemical	Lifetime excess cancer risk resulting from single pathway exposure
Noncancer Effects	Ingestion HQ by pathway and chemical	Ingestion HQ resulting from single pathway exposure
	Ingestion HQ based on drinking water action level for lead and copper	Lead and copper ingestion HQ resulting from drinking water pathway
	Average daily dose for fish consumption for lead	Lead exposure resulting from fish ingestion pathway

Cancer risks for arsenic were characterized using lifetime excess cancer risk estimates, which represent the excess probability of developing cancer over a lifetime as a result of exposure to the chemical of interest. Lifetime excess cancer risk estimates use the LADD (see Section 3.6.3) as the exposure metric. Lifetime excess cancer risk estimates are the product of

the LADD for a specific receptor and the corresponding cancer slope factor, as shown in Equation 3-4.

$$Lifetime\ excess\ cancer\ risk_i = LADD_i \times CSF \tag{3-4}$$

where

LADD = lifetime average daily dose for ingestion pathway i (mg/kg BW/d)
i = pathway index
CSF = cancer slope factor $(mg/kg\ BW/d)^{-1}$.

Noncancer risk is characterized through the use of HQs, which are generated by dividing an ADD (see Section 3.6.3) for ingestion pathways by the corresponding RfD.[7] An HQ establishes whether a particular individual has experienced exposure above a threshold for a specific health effect. Therefore, unlike cancer risk estimates, HQs are not probability statements. Rather, the RfD represents an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. It can be derived from a no observed adverse effect level (NOAEL), from a low observed adverse effect level (LOAEL), or from a benchmark dose, with uncertainty factors generally applied to reflect limitations of the data used. Equation 3-5 shows the calculation for the ingestion HQ. This calculation was completed for each pathway considered (i.e., drinking water ingestion and fish consumption).

$$HQ_i = \frac{ADD_i}{RfD} \tag{3-5}$$

where

ADD_i = average daily dose for ingestion pathway i (mg/kg-d)
i = pathway index
RfD = reference dose (mg/kg-d).

The risk results address risk from exposure via the groundwater-to-drinking-water and groundwater-to-surface-water pathway separately. This is appropriate because the resident consuming contaminated groundwater may not be the recreational fisher who is consuming contaminated fish. Also, the arrival time of the contaminant plume to the stream and the human receptor may not be the same for a particular iteration.[8] However, a resident may consume fish caught from a nearby stream or lake and contaminated drinking water if the travel times are similar, so that possibility should be considered as an uncertainty in this analysis.

For each receptor type, lifetime excess cancer risk estimates for arsenic were calculated separately for the drinking water and fish consumption pathways.

[7] HQs calculated for lead in drinking water were based on the drinking water action level (0.015 mg/L); lead exposures from fish ingestion are reported as an ADD.

[8] Stream distance and well distance were sampled independently in the Monte Carlo analysis.

3.8.2 Ecological Risk Estimation

The full-scale analysis addressed two routes of exposure for ecological receptors: direct contact with contaminated media and ingestion of contaminated food items. HQs were calculated using chemical-specific media concentrations assumed to be protective of ecological receptors of concern through either exposure route (CSCLs). As described in Section 3.7.2, these ecological benchmarks were developed for representative organisms and communities in each environmental medium of concern.

For a particular Monte Carlo iteration, HQs were calculated for sediment and surface water as the ratio between the media concentration and the ecological benchmark. Because the CSCLs were derived for an HQ of 1 (for relevant ecological endpoints), the ratio of a constituent concentration in a media to the media-specific CSCL represents the HQ for that constituent and pathway. For surface water, the HQ was calculated as follows:

$$HQ_{surface\ water} = C_{sw} / CSCL_{sw} \tag{3-6}$$

where

C_{sw} = total concentration in surface water column (mg/L)
$CSCL_{sw}$ = ecological benchmark for surface water (mg/L).

Similarly, for sediment, the HQ was calculated as

$$HQ_{sediment} = C_{sediment} / CSCL_{sediment} \tag{3-7}$$

where

$C_{sediment}$ = total concentration in sediment (mg/kg)
$CSCL_{sediment}$ = ecological benchmark for sediment (mg/kg).

Because the sediment and surface water benchmarks were based on separate receptor communities, it is not appropriate to add HQs across pathways.

4.0 Risk Characterization

This section summarizes the results of the full-scale Monte Carlo analysis and characterizes those results in terms of significant uncertainties and the scenarios and factors that influence risks to human health and the environment. Results are presented by receptor, pathway, and WMU type.

An overview of the assessment on which these results are based (e.g., waste management scenarios, analysis framework) is provided in Section 2. Section 3 provides more details on analysis methodologies, parameter values, and assumptions. In this section, Section 4.1 presents results from the human health risk assessment and includes an analysis of how liner conditions influence results. Section 4.2 presents the results from the ecological risk assessment. Tables summarizing the human and ecological results are presented in each section. Section 4.3 describes the sensitivity analysis conducted for the CCW risk assessment, and Section 4.4 discusses how variability and uncertainty have been addressed, including a semi-quantitative review of the potential impact of some of the more significant uncertainties on results.

Probabilistic results are based on a Monte Carlo simulation in which many model input parameter values were varied over 10,000 iterations of the model per waste management scenario to yield a statistical distribution of exposures and risks. Per the *Guidance for Risk Characterization* developed by the EPA Science Policy Council in 1995 (http://www.epa.gov/OSA/spc/pdfs/rcguide.pdf), EPA defined the high end of the risk distribution at the 90th percentile risk or hazard estimate generated during the Monte Carlo simulation. Thus, the 90th percentile risk results are shown in this section as the high end estimate of the risk distribution generated during the Monte Carlo simulation of constituent release, fate and transport, and exposure associated with CCW disposal in landfills and surface impoundments. In addition, the 50th percentile results are presented as the central tendency estimate of that risk distribution.

For exposure scenarios describing the waste management unit type (e.g., lined landfill; unlined surface impoundment), location (e.g., meteorological region), receptor (e.g., child), and health endpoint (e.g., cancer), the 90th percentile risk represents the high-end estimate that is compared to the appropriate risk criteria (for cancer or noncancer) to help determine whether CCW disposal practices are protective of public health. The risk criteria used are defined in terms of estimated lifetime cancer risk and noncancer hazard attributable to CCW disposal. The risk criteria adopted for this assessment are

- For chemical constituents that cause cancer (carcinogens), the criterion is an estimated excess lifetime cancer risk for exposed individuals of 1 case in 100,000 (i.e., $1x10^{-5}$)
- For constituents that cause adverse, noncancer health effects (noncarcinogens), the criterion is a HQ of greater than 1, with the HQ being the ratio of the average daily

exposure level to a protective exposure level corresponding to the maximum level at which no appreciable effects are likely to occur.

In general, the full-scale analysis showed lower risks than the screening analysis, but still showed risks above risk criteria for certain CCW constituents, WMU types, pathways, and receptors at the 90th percentile. At the 50th percentile, risks are still above the risk criteria for both WMU types, but for fewer constituents and pathways. The results presented herein are subject to further interpretation, as EPA queries the CCW risk inputs and outputs to investigate how the results may be affected by (1) waste types and environmental and waste management conditions, (2) assumptions made about these conditions in designing the probabilistic analysis, and (3) the availability of facility data.

4.1 Human Health Risks

This section presents the 90th and 50th percentile risk results for the two human exposure pathways evaluated in the full-scale analysis: (1) groundwater-to-drinking-water and (2) groundwater-to-surface-water (fish consumption). Results are presented for the two WMU types addressed in the analysis: landfills and surface impoundments, and show the distribution of risks across all waste types by liner type (from the EPRI survey data). The human health risk criteria for the analysis were a 10^{-5} excess cancer risk for arsenic and an HQ greater than 1 for the other constituents, each of which exhibits noncarcinogenic effects.

4.1.1 Groundwater-to-Drinking-Water Pathway

Tables 4-1 and 4-2 present the 90th and 50th percentile risk results, respectively, for the groundwater-to-drinking water pathway for landfills and surface impoundments. Results are shown across all units combined (i.e., across all liner types), as well as for each of the three unit types modeled in the analysis (unlined, clay-lined, and composite-lined). Except for arsenic, the results presented are for a child resident, because those risks for noncarcinogens were consistently higher than the risks for the adult resident. For arsenic, a carcinogen, adult risks are presented because the longer exposure duration and higher intake rates cause risks to be slightly higher for adults than for children. Results for arsenic and selenium are based on the arsenic III and selenium VI species, which are more mobile in soil and groundwater (causing higher receptor well concentrations). Results for other arsenic and selenium species for comparison can be found in the model uncertainty discussion in Section 4.4.2.

Figures 4-1 and 4-2 show the 90th and 50th percentile risk results. For each constituent, the graphs plot the 90th percentile (Figure 4-1) or 50th percentile (Figure 4-2) HQ or cancer risk level against the risk criteria (10^{-5} cancer risk or an HQ greater than 1) by the liner types reported in the EPRI survey. As in the table, the constituents are shown in order from highest risk in the full-scale analysis to lowest; the risk criteria are shown by the solid vertical line. Composite liners are not plotted in these figures when risks are below the x-axis minimum.

Note that not all 12 chemicals modeled in the full-scale assessment are presented for each pathway/WMU scenario. Only the chemicals for which the risks in the screening assessment exceeded the screening criteria for the scenario and for which constituent data were adequate to model and assess risks were modeled in the full-scale assessment, and only those modeled

chemical/pathway/WMU scenarios are shown in the tables and figures. For example, antimony and thallium risks are not presented for surface impoundments because of a high proportion of nondetects in the surface impoundment data for these CCW constituents. Similarly, adequate cobalt data were available only for surface impoundments. Screening-level human health risks for barium were below the screening criteria; therefore, barium is shown only in the ecological risk tables and figures. The screening analysis results in Section 2.1 and Table 2-3 show which CCW constituents were modeled for each pathway/WMU scenario.

Table 4-1. Summary of 90th Percentile Full-Scale CCW Human Risk Results: Groundwater-to-Drinking-Water Pathway

Chemical[b]	90th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[c]	Unlined Units	Clay–Lined Units	Composite–Lined Units
Landfills				
Arsenic (cancer)	3E-04	5E-04	2E-04	0
Thallium	2	3	1	0
Antimony	0.7	1	0.6	0
Molybdenum	0.9	1	0.7	0
Lead (MCL)[d]	0.4	0.9	0.2	0
Cadmium	0.2	0.3	0.2	0
Boron	0.3	0.5	0.3	0
Selenium	0.2	0.4	0.2	0
Nitrate/Nitrite (MCL)[d]	0.1	0.2	0.07	3E-06
Surface Impoundments				
Arsenic (cancer)	6E-03	9E-03	3E-03	4E-07
Molybdenum	4	5	3	7E-03
Cobalt	4	5	0.9	0
Cadmium	4	5	1	2E-09
Lead (MCL)[d]	3	5	0.9	1E-20
Boron	3	3	2	4E-03
Selenium	1	1	0.8	1E-03
Nitrate/Nitrite (MCL)[d]	0.9	1	1	6E-04

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that not every chemical that was selected for full-scale modeling was modeled in every pathway/WMU scenario: only chemicals with adequate data and that were identified in the screening analysis as needing further assessment (see Section 2.1) were modeled for each scenario.

[c] Results across all unit types combined (unlined, clay-lined, and composite-lined).

[d] Values are ratios of exposure concentration to MCL.

Table 4-2. Summary of 50th Percentile Full-Scale CCW Human Risk Results: Groundwater-to-Drinking-Water Pathway

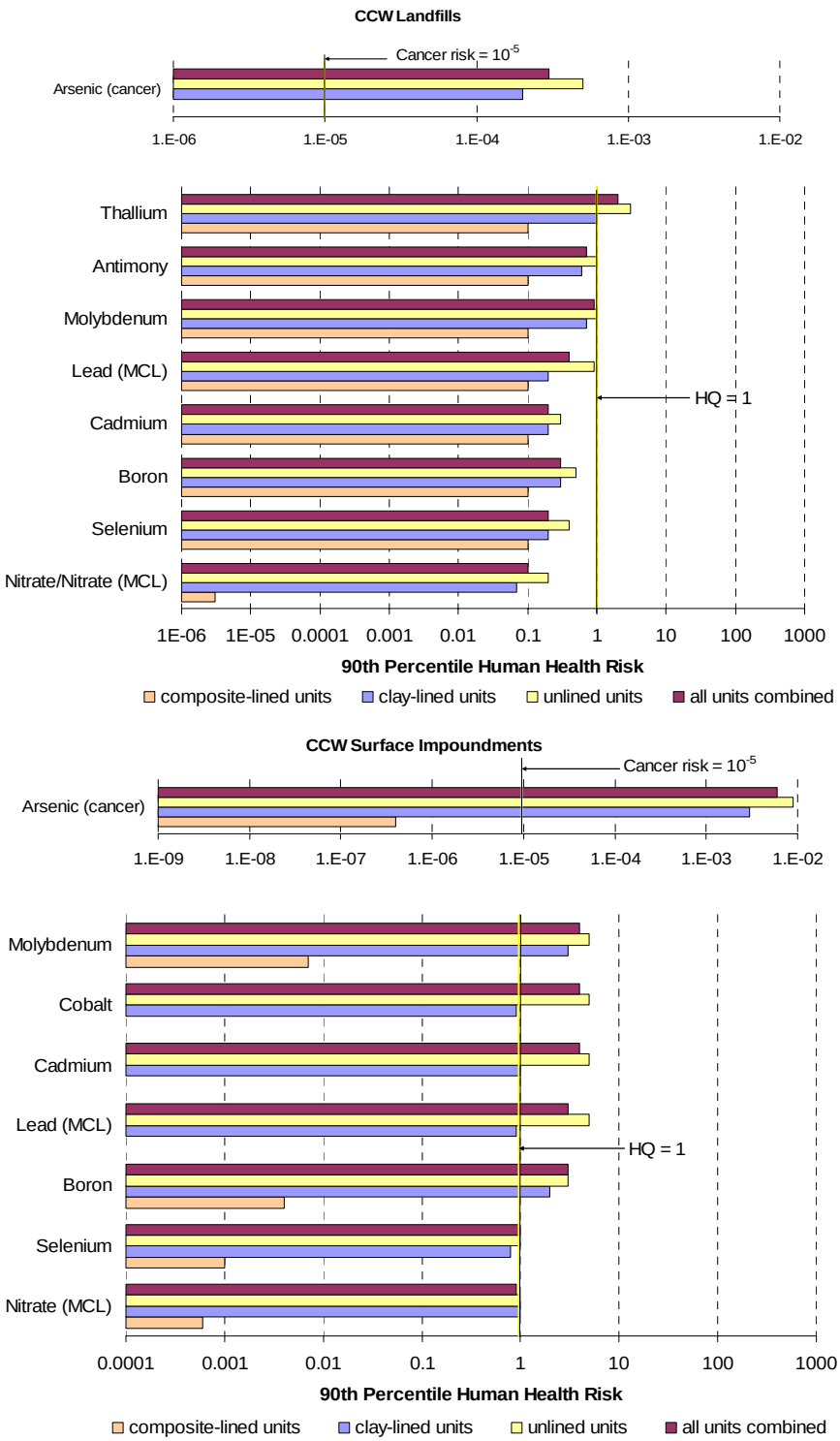
Chemical[b]	50th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[c]	Unlined Units	Clay–Lined Units	Composite–Lined Units
Landfills				
Arsenic (cancer)	3E-06	1E-05	5E-06	0
Thallium	0.07	0.2	0.09	0
Antimony	0.01	0.05	0.02	0
Molybdenum	0.01	0.03	0.02	0
Lead (MCL)[d]	2E-07	5E-03	6E-08	0
Cadmium	4E-03	0.01	6E-03	0
Boron	4E-03	0.01	7E-03	0
Selenium	6E-03	0.02	8E-03	0
Nitrate/Nitrite (MCL)[d]	4E-03	0.01	5E-03	0
Surface Impoundments				
Arsenic (cancer)	1E-04	3E-04	9E-05	0
Molybdenum	0.6	0.9	0.4	5E-12
Cobalt	9E-03	0.02	3E-03	0
Cadmium	0.06	0.08	0.03	0
Lead (MCL)[d]	0.05	0.09	9E-03	0
Boron	0.1	0.2	0.1	6E-12
Selenium	0.08	0.1	0.05	5E-12
Nitrate/Nitrite (MCL)[d]	0.03	0.04	0.02	7E-08

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that not every chemical that was selected for full-scale modeling was modeled in every pathway/WMU scenario: only chemicals with adequate data and that were identified in the screening analysis as needing further assessment (see Section 2.1) were modeled for each scenario.

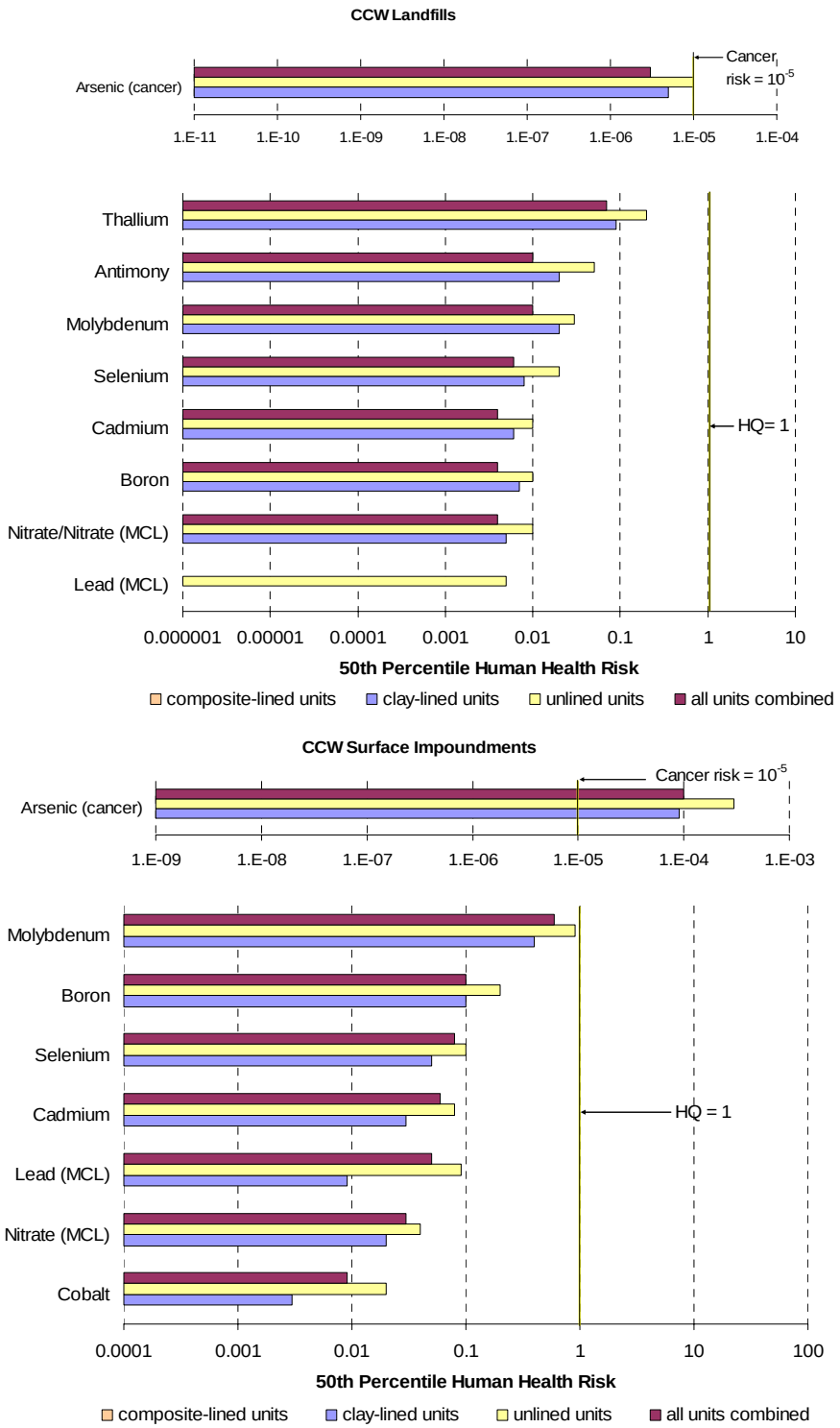
[c] Results across all unit types combined (unlined, clay-lined, and composite-lined).

[d] Values are ratios of exposure concentration to MCL.



A cancer risk of 10^{-5} or an HQ greater than 1 are the risk criteria for this analysis.
Results for "all units combined" are results across all liner types (unlined, clay-lined, composite-lined).
Note: When the composite liner bar does not appear on the chart, the 90th percentile risk index is below the minimum shown on the x-axis.

Figure 4-1. Full-scale 90th percentile risk results for the groundwater-to-drinking-water pathway.



A cancer risk of 10^{-5} or an HQ greater than 1 are the risk criteria for this analysis.
Results for "all units combined" are results across all liner types (unlined, clay-lined, composite-lined).
Note: When the composite liner bar does not appear on the chart, the 50th percentile risk index is below the minimum shown on the x-axis.

Figure 4-2. Full-scale 50th percentile risk results for the groundwater-to-drinking-water pathway.

As can be seen in Figure 4-1, the full-scale analysis produced lower risks for landfills than surface impoundments. For landfills, at the 90th percentile, arsenic shows risks above a cancer risk of $1x10^{-5}$ for both unlined units ($5x10^{-4}$) and clay-lined units ($2x10^{-4}$) and thallium shows a noncancer risk (3) above an HQ of 1 only for unlined units. Figure 4-2 shows that at the 50th percentile, all risks were at or below the risk criteria. Composite-lined units show zero or negligible risks (well below the risk criteria) for all constituents and percentiles examined.

For surface impoundments, the full-scale analysis produced arsenic risk estimates at the 90th percentile above a cancer risk of $1x10^{-5}$ for both unlined units ($9x10^{-3}$) and clay-lined units ($3x10^{-3}$) and a noncancer HQ above the criteria for boron (3), lead (5), cadmium (5), cobalt (5), and molybdenum (5) for unlined units, and for boron (2) and molybdenum (3) for clay-lined units. At the 50th percentile, only arsenic has risks above the 10^{-5} risk criterion for unlined ($3x10^{-4}$) and clay-lined ($9x10^{-5}$) surface impoundments. And as with landfills, the risks from composite-lined surface impoundments are well below the risk criteria.

The higher risks for surface impoundments as compared to landfills reflect higher constituent concentrations in the surface impoundment wastes, a higher proportion of unlined units (see Section 4.1.4), and a higher hydraulic head in an impoundment that drives leachate into the underlying soil with greater force than infiltration in landfills. This higher head results in a greater flux of contaminants to groundwater during the active life of the surface impoundment, especially in unlined units. In combination with the higher CCW constituent concentrations in surface impoundment porewater and a greater proportion of unlined units, these factors lead to more and higher risk exceedances for surface impoundments than for landfills.

The analysis demonstrates that the presence of liners, especially composite liners, reduce leaching and risks from CCW landfills and surface impoundments. Note that 90th percentile risks from composite liners are zero for most constituents for landfills, which means that in 90 percent of the cases, the contaminant did not reach the receptor well in the 10,000 year limit for this analysis. These zero values reflect the liner leakage rates in the empirical data set used to develop composite landfill liner infiltration rates used in this risk assessment (from U.S. EPA, 2002b; see Section 3.2.2), which are mostly zero values or very low in terms of infiltration rate. Although these infiltration rates are based on the best data available to EPA, these data are not specific to CCW facilities and therefore represent an uncertainty in this analysis (see Sections 3.2.2 and 4.4.3.2).

Composite liners also significantly reduced risks for surface impoundments for several constituents at the 90th percentile by 4 to 10 orders of magnitude and generated risk results well below the risk criteria for this analysis. Infiltration rates for composite-lined surface impoundments are largely controlled by leak density (see Section 3.3), which is an empirical distribution from the same source as the landfill infiltration rates (U.S. EPA, 2002b), and are subject to similar uncertainties.

Arrival times for the peak arsenic concentration used to calculate risks are plotted as cumulative distributions for surface impoundments and landfills in Figure 4-3. As can be seen in the figure, the peak arrival time for surface impoundments is usually less than 100 years (i.e., peak concentration occurs shortly after closure); the 50th percentile is 78 years, and the 75th

percentile is 105 years.[2] Arrival times for landfills are much longer, ranging from hundreds to thousands of years; the 50th percentile is 618 years and the 75th percentile is 3,343 years. The shorter arrival times for surface impoundments are primarily due to the hydraulic head of the waste liquids in the unit and the lower prevalence of liners in surface impoundments; by contrast, landfill leaching is driven by infiltration of precipitation through the cap and liner of the unit.

The arrival time of the peak concentration corresponds to the arrival of the maximum risk; however, for runs where the risk exceeds the risk criteria, the concentration that results in risk at the risk criteria will arrive somewhat before the peak concentration. Overall, however, the time to reach the risk criteria should be similar to the peak arrival times shown in Figure 4-3.

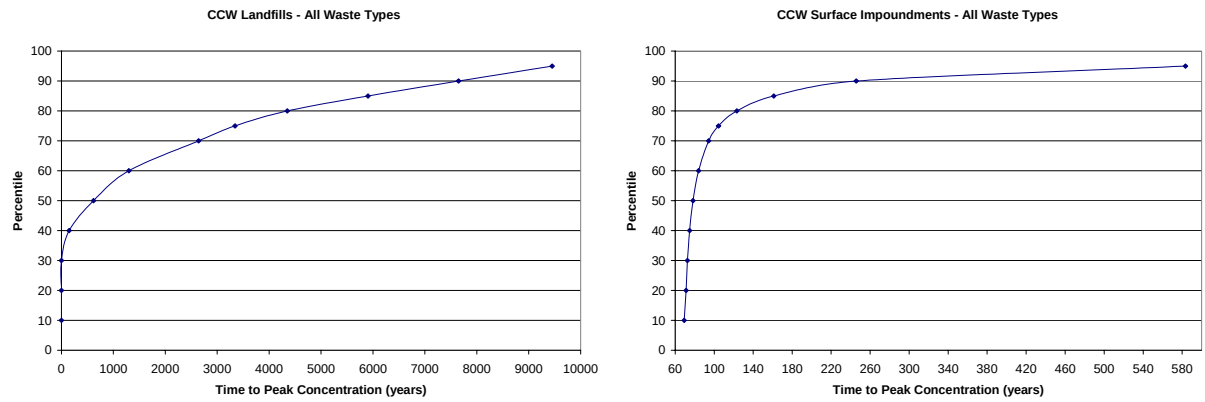


Figure 4-3. Comparison of peak arrival times for arsenic for CCW landfills and surface impoundments.

4.1.2 Groundwater-to-Surface-Water (Fish Consumption) Pathway

Tables 4-3 and 4-4 present the 90th and 50th percentile risk results, respectively, for the fish consumption pathway, where fish are contaminated by groundwater seeping into a waterbody downgradient from the WMU. The results presented are for a fisher's child because those risks were consistently higher than the risks for the adult fisher. Results for arsenic are based on arsenic III, which is more mobile in soil and groundwater (and so had higher receptor concentrations). The selenium results are based on selenium VI, which also represents the highest receptor concentrations. The uncertainty resulting from the model's inability to speciate metals during transport is discussed in Section 4.4.2.

For surface impoundments, 90th percentile selenium and arsenic risks for unlined units are slightly above a cancer risk of $1x10^{-5}$ ($2x10^{-5}$, arsenic) and slightly above a noncancer HQ of 1 (2 for selenium). Risks are below the risk criteria for clay-lined and composite-lined surface impoundments. Again, risks are higher for surface impoundments than for landfills (where risks are below risk criteria for all constituents) because of the higher waste concentrations, higher hydraulic head in these units, and a lower prevalence of liners, as discussed previously for the drinking water pathway. Fish consumption pathway 50th percentile results are well below the risk criteria for all constituents, waste management scenarios, and liner types.

[2] In other words, 50 percent of the arrival times are less than 78 years and 75 percent are less than 105 years.

As with the groundwater-to-drinking-water pathway analysis, the absence of risk from composite-lined units suggests that the composite liners modeled in this analysis are effective at preventing contaminants from reaching the surface waterbodies of interest.

Table 4-3. Summary of 90th Percentile Full-Scale CCW Human Risk Results: Groundwater-to-Surface-Water (Fish Consumption) Pathway

Chemical[b]	90th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined [c]	Unlined Units	Clay-Lined Units	Composite–Lined Units
Landfills				
Arsenic (cancer)	6E-07	1E-06	3E-07	0
Selenium	0.3	0.7	0.1	0
Thallium	0.2	0.4	0.07	0
Cadmium	0.02	0.06	9E-03	0
Surface Impoundments				
Arsenic (cancer)	1E-05	2E-05	7E-06	6E-13
Selenium	2	2	1	2E-06
Cadmium	0.1	0.2	0.09	3E-15

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that not every chemical that was selected for full-scale modeling was modeled in every pathway/WMU scenario: only chemicals with adequate data and that were identified in the screening analysis as needing further assessment (see Section 2.1) were modeled for each scenario.

[c] Results across all unit types combined (unlined, clay-lined, and composite-lined).

Table 4-4. Summary of 50th Percentile Full-Scale CCW Human Risk Results: Groundwater-to-Surface-Water (Fish Consumption) Pathway

Chemical[b]	50th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[c]	Unlined Units	Clay–Lined Units	Composite–Lined Units
Landfills				
Arsenic (cancer)	6E-11	1E-09	3E-10	0
Selenium	5E-05	7E-04	2E-04	0
Thallium	3E-05	5E-04	2E-04	0
Cadmium	2E-06	5E-05	8E-06	0
Surface Impoundments				
Arsenic (cancer)	2E-08	5E-08	3E-09	0
Selenium	3E-03	7E-03	4E-04	0
Cadmium	3E-04	9E-04	3E-05	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

[b] Note that not every chemical that was selected for full-scale modeling was modeled in every pathway/WMU scenario: only chemicals with adequate data and that were identified in the screening analysis as needing further assessment (see Section 2.1) were modeled for each scenario.

[c] Results across all unit types combined (unlined, clay-lined, and composite-lined).

4.1.3 Results by Waste Type/WMU Scenario

As described in Section 3.1, the CCW risk assessment was organized by waste type so that different waste chemistries could be accounted for in the fate and transport modeling. The results discussed so far in this report address conventional CCW (fly ash, bottom ash, boiler slag, FGD sludge) and conventional CCW codisposed with coal refuse.[3] Section 4.1.3.1 presents these results by waste type. FBC wastes were also modeled in this assessment, but because of the small number of FBC waste disposal sites (7) in the EPRI/EPA database, the results are treated separately in Section 4.1.3.2.

4.1.3.1 Conventional CCW and CCW Codisposed with Coal Refuse

Tables 4-5 and 4-6 show 90th- and 50th-percentile risk results, respectively, by waste type and unit type for CCW landfills for the groundwater-to-drinking-water pathway. There was little difference in results between waste types for landfills, which showed very similar risks for conventional CCW and codisposed CCW and coal refuse. Risks are a factor of 2 or 3 greater for unlined landfills than for clay-lined landfills. For conventional CCW in landfills, arsenic cancer risks are $4x10^{-4}$ for unlined units, $2x10^{-4}$ for clay-lined units, and 0 for composite-lined units at

[3] Coal refuse is the waste coal produced from coal handling, crushing, and sizing operations, and tends to have a high sulfur content and low pH. In the CCW constituent database, codisposed coal refuse includes “combined ash and coal gob,” “combined ash and coal refuse,” and “combined bottom ash and pyrites.”

the 90th percentile. Noncancer risks at the 90th percentile exceeded 1 for only thallium in unlined units (3) and clay-lined units (2) and antimony in unlined units (2). For codisposed CCW and coal refuse in landfills, arsenic cancer risks are $5x10^{-4}$ for unlined units, $2x10^{-4}$ for clay-lined units, and 0 for composite-lined units at the 90th percentile. Noncancer hazard quotients at the 90th percentile exceeded 1 for only thallium in unlined units (2) and molybdenum in unlined units (2). 50th percentile risks for the groundwater-to-drinking-water pathway were below the risk criteria for all waste types in all types of landfills. Landfills with composite liners show zero risks as modeled in this assessment (see Section 4.1.4 for a further discussion of risks by liner type).

The difference in risks between waste types is greater for surface impoundments. Tables 4-7 and 4-8 show 90th and 50th percentile risk results, respectively, by waste type and liner type for CCW surface impoundments (for the drinking water pathway). For conventional CCW in surface impoundments, arsenic cancer risks are $2x10^{-3}$ for unlined units, $9x10^{-4}$ for clay-lined units, and below the risk criteria for composite-lined units at the 90th percentile. Noncancer hazard quotients at the 90th percentile exceeded 1 for nitrate/nitrite (20), molybdenum (8), boron (7), selenium (2), and lead (3) in unlined units, and nitrate/nitrite (10), molybdenum (5) and boron (4) in clay-lined units. None of the risk criteria were exceeded at the 90th percentile in composite-lined units. For codisposed CCW and coal refuse in surface impoundments, arsenic cancer risks are $2x10^{-2}$ for unlined units, $7x10^{-3}$ for clay-lined units, and below the risk criteria for composite-lined units at the 90th percentile. Noncancer hazard quotients at the 90th percentile exceeded 1 for cadmium (9), cobalt (8), lead (9), and molybdenum (3) in unlined units, and cadmium (3), cobalt (3), and molybdenum (2) in clay-lined units. None of the risk criteria were exceeded at the 90th percentile in composite-lined units. As noted above, codisposal of CCW and coal refuse in surface impoundments results in risks up to 10-fold greater than those seen for conventional CCW managed in surface impoundments. This is likely due to the higher metal concentrations and the acidity of coal refuse leachate[4] for surface impoundments in the CCW database. As with landfills, clay-lined units show lower risks by a factor of 2 or 3 than unlined units, and composite liners show negligible or zero risks for either waste type.

[4] Metals tend to show greater solubility and mobility in acidic leachate.

Table 4-5. 90th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 79 landfills				
Arsenic (cancer)	3E-04	4E-04	2E-04	0
Thallium	2	3	2	0
Antimony	1	2	0.8	0
Molybdenum	0.9	1	0.8	0
Lead (MCL)[b]	0.5	1	0.3	0
Cadmium	0.4	0.7	0.4	0
Boron	0.4	0.7	0.4	0
Selenium	0.1	0.2	0.1	0
Nitrate/nitrite (MCL)[c]	0.07	0.1	0.06	2E-06
Codisposed CCW and Coal Refuse – 41 landfills				
Arsenic (cancer)	3E-04	5E-04	2E-04	0
Thallium	1	2	1	0
Molybdenum	0.8	2	0.6	0
Antimony	0.5	0.8	0.3	0
Selenium	0.4	0.7	0.3	0
Lead (MCL)[c]	0.3	0.7	0.09	0
Boron	0.2	0.3	0.1	0
Nitrate/nitrite (MCL)[c]	0.2	0.2	0.1	3E-06
Cadmium	0.1	0.2	0.07	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.
[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).
[c] Values are ratios of exposure concentration to MCL.

Table 4-6. 50th Percentile Risk Results by CCW Type: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	50th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 79 landfills				
Arsenic (cancer)	2E-06	6E-06	4E-06	0
Thallium	0.08	0.2	0.1	0
Antimony	0.02	0.04	0.02	0
Molybdenum	0.03	0.05	0.04	0
Lead (MCL)[b]	3E-08	4E-04	2E-08	0
Cadmium	0.005	0.01	0.008	0
Boron	0.007	0.01	0.01	0
Selenium	0.004	0.009	0.006	0
Nitrate/nitrite (MCL)[c]	0.002	0.004	0.003	0
Codisposed CCW and Coal Refuse – 41 landfills				
Arsenic (cancer)	4E-06	2E-05	6E-06	0
Thallium	0.06	0.2	0.07	0
Molybdenum	0.006	0.02	0.006	0
Antimony	0.01	0.05	0.02	0
Selenium	0.008	0.03	0.01	0
Lead (MCL)[c]	6E-07	0.01	2E-07	0
Boron	0.002	0.008	0.003	0
Nitrate/nitrite (MCL)[c]	0.01	0.04	0.009	0
Cadmium	0.003	0.02	0.004	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.
[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).
[c] Values are ratios of exposure concentration to MCL.

Table 4-7. 90th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Drinking-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite-Lined Units
Conventional CCW – 44 surface impoundments				
Arsenic (cancer)	1E-03	2E-03	9E-04	2E-07
Nitrate/nitrite (MCL)[c]	10	20	10	9E-04
Molybdenum	6	8	5	7E-03
Boron	5	7	4	5E-03
Selenium	2	2	1	1E-03
Lead (MCL)[c]	1	3	0.7	1E-21
Cadmium	0.4	0.5	0.3	4E-11
Cobalt	0.01	0.01	6E-03	0
Codisposed CCW and Coal Refuse – 72 surface impoundments				
Arsenic (cancer)	2E-02	2E-02	7E-03	4E-06
Cadmium	8	9	3	5E-05
Cobalt	7	8	3	4E-08
Lead (MCL)[c]	6	9	1	1E-19
Molybdenum	3	3	2	4E-03
Boron	1	1	0.5	2E-03
Selenium	0.8	0.8	0.4	1E-03
Nitrate/nitrite (MCL)[c]	0.3	0.4	0.2	1E-04

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.
[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).
[c] Values are ratios of exposure concentration to MCL.

Table 4-8. 50th Percentile Risk Results by CCW Type: Surface Impoundments, Groundwater-to-Drinking-Water Pathway

Chemical	50th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite–Lined Units
Conventional CCW – 44 surface impoundments				
Arsenic (cancer)	7E-05	1E-04	6E-05	0
Nitrate/nitrite (MCL)[c]	0.05	0.1	0.05	7E-08
Molybdenum	0.6	1.1	0.5	2E-11
Boron	0.2	0.4	0.2	3E-11
Selenium	0.07	0.1	0.07	2E-11
Lead (MCL)[c]	0.02	0.05	0.007	0
Cadmium	0.03	0.05	0.02	0
Cobalt	0.001	0.003	8E-04	0
Codisposed CCW and Coal Refuse – 72 surface impoundments				
Arsenic (cancer)	4E-04	6E-04	2E-04	0
Cadmium	0.1	0.1	0.05	0
Cobalt	0.3	0.4	0.09	0
Lead (MCL)[c]	0.09	0.1	0.01	0
Molybdenum	0.6	0.8	0.3	3E-18
Boron	0.1	0.1	0.06	5E-15
Selenium	0.08	0.1	0.03	5E-15
Nitrate/nitrite (MCL)[c]	0.02	0.03	0.01	4E-08

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.
[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).
[c] Values are ratios of exposure concentration to MCL.

4.1.3.2 FBC Wastes

Tables 4-9 and 4-10 show the 90th- and 50th-percentile risk results for FBC landfills by unit type. At the 90th percentile in landfills, arsenic cancer risks are $3x10^{-5}$ for unlined units, $6x10^{-5}$ for clay-lined units, and 0 for composite-lined units. Noncancer hazard quotients exceed 1 for only thallium (4) and antimony (3) in clay-lined units. No risks exceeded the risk criteria at the 50th percentile. These results suggest lower risks than for conventional CCW and CCW codisposed with coal refuse. The difference may be attributed to lower FBC leachate concentrations and the alkaline nature of FBC waste.

Note that clay-lined FBC landfills show higher risks than unlined facilities, which is counterintuitive considering how clay-lined and unlined units are designed and operated. This

result reflects the characteristics of the limited number and locations of FBC landfills[5] and illustrates how the probabilistic analysis design and availability of facility data can impact risk results (and why FBC results are treated separately in the risk characterization). As presented in Section 3.1.2 and in Figure 3-2, the Monte Carlo analysis was designed to evaluate risks posed by current waste management practices for a given WMU type, waste type, and waste constituent. This approach limits the effects of data availability for the different liner configurations when the risks are aggregated over all units (lined and unlined) combined. However, when the risk results of an exposure pathway are viewed at a resolution finer than the analysis design, a small sample size for a particular waste and WMU type scenario (as occurs for FBC waste), along with the interactions of liner type with other site-based inputs (notably infiltration rate and the size of the WMU), can produce unexpected results. In the case of FBC wastes, the characteristics (primarily infiltration rate and areas) of the three unlined landfills were such that their risks were lower than the clay-lined FBC landfills.

Table 4-9. 90th Percentile Risk Results for FBC Wastes: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	90th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite-Lined Units
FBC Waste – 7 landfills				
Arsenic (Cancer)	4E-05	3E-05	6E-05	0
Thallium	2	1	4	0
Antimony	1	0.8	3	0
Lead (MCL)[c]	0.4	0.4	0.6	0
Molybdenum	0.3	0.2	0.5	0
Cadmium	0.2	0.1	0.3	0
Selenium	0.1	0.08	0.1	0
Nitrate/nitrite (MCL)[c]	0.05	0.03	0.07	5E-08
Boron	0.04	0.02	0.07	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000-year period of the analysis.
[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).
[c] Values are ratios of exposure concentration to MCL.

[5] FBC WMU data were available for only seven landfills (3 unlined, 3 clay-lined, and 1 composite-lined), and it is not known how representative these data are with respect to WMU characteristics and locations throughout the United States.

Table 4-10. 50th Percentile Risk Results for FBC Wastes: Landfills, Groundwater-to-Drinking-Water Pathway

Chemical	50th Percentile HQ or Cancer Risk Value[a]			
	All Units Combined[b]	Unlined Units	Clay-Lined Units	Composite-Lined Units
FBC Waste – 7 landfills				
Arsenic (Cancer)	0	0	4E-07	0
Thallium	0.008	0	0.2	0
Antimony	0.002	0	0.09	0
Lead (MCL)[c]	0	0	2E-04	0
Molybdenum	0.003	0	0.04	0
Cadmium	4E-07	0	0.01	0
Selenium	3E-04	0	0.01	0
Nitrate/nitrite (MCL)[c]	1E-04	3E-08	0.004	0
Boron	2E-04	0	0.003	0

[a] Values are HQs for all chemicals except arsenic; arsenic values are cancer risk. Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000-year period of the analysis.
[b] HQ or risk across all unit types combined (unlined, clay-lined, and composite-lined).
[c] Values are ratios of exposure concentration to MCL.

4.1.4 Results by Unit Type

The effect of unit type on human health risk for the groundwater-to-drinking-water pathway can be seen in Tables 4-1 and 4-2, which compare 90th and 50th percentile risks, respectively, for WMUs that are unlined, clay lined, and lined with composite liners from the 1995 EPRI survey data (EPRI, 1997). At the 90th percentile, lined units produced lower risk estimates than unlined units for all constituents modeled. Composite liners produced very low to zero risk estimates as compared to clay liners for all constituents modeled for both landfills and surface impoundments. For surface impoundments, clay liners produced higher risk estimates for all constituents as compared to clay liners in landfills. Similar trends are evident at the 50th percentile, where composite liners produced risk estimates of zero or near zero for all constituents for surface impoundments.

Table 4-11 shows the frequency of each of the unit types in the 1995 EPRI survey data modeled in this analysis, and it compares these data with the unit type frequency in the more recent DOE/EPA study (U.S. DOE, 2006). The 56 WMUs surveyed in the U.S. DOE 2006 study were commissioned between 1994 and 2004. Although the actual number of WMUs that were established in that timeframe cannot be verified, based on proxy data (i.e., CCW available for disposal in those states with identified, new WMUs and coal-fired power plant generating capacity), the sample coverage is estimated to be at least between 61 and 63 percent of the total

population of the newly commissioned WMUs.[6] With the exception of one landfill, the newly constructed facilities are all lined, with either clay, synthetic, or composite liners. The single unlined landfill identified in the recent DOE report receives bottom ash, which is characterized as an inert waste by the state, and therefore, a liner is not required. As Table 4-11 shows, there is a marked trend away from unlined WMUs in favor of lined units, with a distinct preference for synthetic or composite liners. Comparison of the 26 coal combustion plants in both the EPRI survey and the DOE/EPA survey (U.S. DOE, 2006) shows that although most of those facilities (17 of 26) were using unlined WMUs in 1995, all 26 are now placing wastes in new or expanded landfills or surface impoundments that are lined with clay, synthetic, or composite liners. However, it is likely that the older unlined units were closed with wastes in place, and that these wastes therefore still pose a threat through groundwater pathways. Also, the number of unlined unit that continue to operate in the United States cannot be determined from the available data.

Table 4-11. Unit Types in EPRI Survey

Liner Type	Landfills	Surface Impoundments
1995 EPRI Survey[a] – 181 facilities		
Unlined	40%	68%
Compacted clay	45%	27%
Synthetic or composite (clay and synthetic)	16%	5%
Total	100%	100%
2004 DOE Survey[b] – 56 Facilities		
Unlined	3%	0%
Compacted clay	29%	17%
Synthetic or composite (clay and synthetic)	68%	83%
Total	100%	100%

[a] EPRI (1997)
[b] U.S.DOE (2006)

As described in Sections 3.2.1 and 3.3.1, the characteristics of the liners used in the CCW risk were taken from the IWEM model as representative of the general performance of each liner type. For landfills, an engineered compacted clay liner (3 feet thick, with a hydraulic conductivity of 1 x 10^{-7} cm/s) reduced the 90th percentile risk by a factor of about 2 to 4 compared to no liner, but did not change the constituents at or above the risk criteria (arsenic and thallium). For surface impoundments, clay liners did reduce the risk to just below the risk criteria for cobalt, lead, and selenium.

Composite (clay and synthetic) liners, as modeled in this risk assessment (see Sections 3.2 and 3.3), were much more effective at reducing risk for all constituents; 90th (and

[6] For additional details as to how these estimates were derived, the reader is referred to the DOE study, pages S-2 – S-3 of the Summary Section and Section 3.1.2..

50th) percentile risks with composite liners for landfills were zero[7] for arsenic and metals and very low or zero for nitrate/nitrite, and were well below the risk criteria for all constituents for surface impoundments. The analysis used data collected for composite liner performance at industrial waste management facilities, including liner leakage rate for landfills and the number of liner perforations for surface impoundments (TetraTech, 2001). Because data on CCW liner leakage rates are not available, there is some uncertainty in applying these Industrial D liner performance data to CCW disposal units. Still, these rates do reflect actual performance data from liners under real WMUs, and they demonstrate that composite liners can be effective in reducing leaching from CCW WMUs and suggest that there will be a significant decrease in risk from CCW disposal if more facilities line their WMUs with composite liners. Information from the more recent DOE/EPA study (U.S. DOE, 2006) indicates that composite liners are much more prevalent in newly constructed facilities, so the risks from CCW disposal should be lower for newer CCW landfills and surface impoundments.

4.1.5 Constituents Not Modeled in the Full-Scale Assessment

As described in Section 2.1.1.2, resources did not allow full-scale modeling to be conducted for all 21 constituents that were above the screening criteria in the initial screening analysis; nine constituents that were judged to likely have generally lower risks to human health and ecological risks were not modeled in the full-scale risk assessment.[8] Five of these chemicals (chromium, fluoride, manganese, vanadium, and nickel) had drinking water pathway HQs in the screening analysis ranging from 1 to less than 6 for surface impoundments, and three (chromium, fluoride, and vanadium) had screening HQs of 2 for landfills.

To address these constituents, we developed surrogate risk attenuation factors by dividing the screening risk results by the full-scale risk results, across all unit types combined, for the constituents modeled in the full-scale assessment. This comparison was done only for the drinking water exposure pathway, the only human health exposure pathway for which the risks for these constituents were above the screening criteria. Table 4-12 shows the risk attenuation factor statistics for the modeled constituents, and Table 4-13 shows the results of applying the median and 10th percentile attenuation factors to the screening risk results for the marginal constituents. Differences in attenuation among the modeled constituents reflects differences in contaminant sorption and mobility. The 10th percentile attenuation factor was selected as a conservative value representing the more mobile constituents, such as arsenic, selenium, and molybdenum. The 50th percentile (or median) risk represents a central tendency value.

For landfills, the risk attenuation factors ranged from 6 to 40, with the lower attenuation factors mainly representing the more mobile constituents (i.e., those with lower soil sorption potential). Both the median and 10th percentile risk attenuation factors were adequate to reduce risks for all nine constituents below an HQ of 1.

[7] The absence of risk indicates that contaminant infiltration rates were too small for the contaminant plume to reach the receptor well during the 10,000 year period of the analysis. See Section 3.2.2 for a discussion of the empirical liner infiltration data used in this analysis.

[8] These constituents of marginal concern had no human health HQs greater than 6 and only one or no ecological HQs greater than 100.

For surface impoundments, risk attenuation factors were considerably lower, ranging from 1 to 9, reflecting higher contaminant mobility due to the higher hydraulic head in surface impoundments (as compared to landfills) and a lower proportion of liners. For the same reason, the screening HQs for surface impoundments were higher than the landfill HQs. As a result of this combination of higher HQs and lower risk attenuation factors, only the HQ for nickel was reduced to below 1 by applying the attenuation factors. The other constituents (chromium, fluoride, manganese, and vanadium) still show risks slightly above the risk criteria, with HQs ranging from 1.4 to 3.5. This is consistent with the general trend in this analysis of surface impoundments showing higher risks and more risks exceeding the risk criteria than CCW landfills.

Table 4-12. Risk Attenuation Factor[a] Statistics for Modeled Constituents—Groundwater to Drinking Water Pathway

Statistic	Landfill	Surface Impoundment
10th percentile	7	1.6
50th percentile	12	2.6
Average	16	3.3
Maximum	40	9.3
Number of data points	9	8

[a] The risk attenuation factor is the ratio of the full-scale analysis risk and screening analysis risk for a constituent modeled in the full-scale analysis.

Table 4-13. Summary of Risk Results for Constituents Using Risk Attenuation Factors—Groundwater-to-Drinking-Water Pathway

WMU/Pathway	Landfill			Surface Impoundment		
	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation
Chromium VI	2.3	0.2	0.3	4.2	1.6	2.6
Fluoride	1.8	0.2	0.3	5.2	2.0	3.3
Manganese	1	0.1	0.1	5.6	2.2	3.5
Vanadium	2.2	0.2	0.3	2.3	0.9	1.4
Nickel	-	-	-	1.3	0.5	0.8

4.2 Ecological Risks

EPA defines ecological risk characterization in terms of (1) the risk estimation, which integrates the exposure and stressor-response profile to estimate the likelihood of adverse ecological effects and (2) the risk description, which synthesizes the overall conclusion of the assessment and addresses assumptions, uncertainty, and limitations.

For assessments that are based on a HQ approach, as this one is, the comparison of modeled exposure concentrations to CSCLs to estimate risk has a binary outcome: either the constituent concentration is above the environmental quality criteria (HQ greater than 1) or the concentration is below the criteria (HQ less than or equal to 1). For the full-scale analysis, an ecological HQ greater than 1 was selected by EPA as a criterion for decision making. Because the CSCLs were based on *de minimis* ecological effects, it is generally presumed that an HQ at or below 1 indicates a low potential for adverse ecological effects for those receptors included in the analysis for which data are available. However, it is important to recognize that although this method provides important insight into the potential for adverse ecological effects, the results are relevant only to those receptors that were included in the assessment and for which data were available. The results have limited utility in interpreting the ecological significance of predicted effects, and caution should be exercised in extrapolating to ecosystems (e.g., wetlands) and receptors (e.g., threatened and endangered species) not explicitly modeled.

This section presents risk results for the two groundwater-to-surface-water ecological exposure pathways investigated in the full-scale analysis: (1) receptors exposed to CCW constituents in the water column (surface water receptors) and (2) receptors exposed to CCW constituents in bed sediment (sediment receptors). Results are presented for the two WMU types addressed in the analysis: landfills and surface impoundments. The ecological risk results are presented for all unit types combined and were not broken out separately for the different unit types.

The ecological risk results suggest the potential for adverse ecological effects to aquatic systems from CCW releases into the subsurface and subsequent connection with surface waters, particularly for CCW managed in unlined surface impoundments. As with human health risks, the higher prevalence of liners in newer facilities should result in lower risks in current and future CCW disposal facilities than those presented in this risk assessment.

4.2.1 Surface Water Receptors

Table 4-14 presents the 90th and 50th percentile results for the groundwater-to-surface-water pathway for surface water receptors for landfills and surface impoundments. For landfills, only boron (200) and lead (4) show HQs above the risk criteria at the 90th percentile. For surface impoundments, boron (2000), lead (20), arsenic (10), selenium (10), cobalt (5), and barium (2) showed 90th percentile risks above the risk criteria. The 50th percentile results are well below an HQ of 1 for landfills and only exceed an HQ of 1 for boron (4) in surface impoundments.

The difference in the number and magnitude of HQs that exceed the risk criterion between landfills and surface impoundments is likely the result of higher CCW constituent concentrations in surface impoundment porewater and the greater flux of contaminants to

groundwater predicted during the active life of the surface impoundment. As discussed in Section 4.1, the higher infiltration rates for surface impoundments result from a higher hydraulic head in the impoundment and a higher proportion of unlined surface impoundments than landfills.

Table 4-14. Summary of Full-Scale CCW Ecological Risk Results: Groundwater-to-Surface-Water Pathway, Aquatic Receptors[a]

Chemical	90th Percentile HQ	50th Percentile HQ	Pathway	Receptor
Landfills				
Boron	200	0.04	direct contact	aquatic biota
Lead	4	2E-08	ingestion	river otter
Selenium	1	3E-04	direct contact	aquatic biota
Arsenic	0.7	9E-10	direct contact	aquatic biota
Barium	0.8	3E-18	direct contact	aquatic biota
Cadmium	0.3	3E-05	direct contact	aquatic biota
Aluminum	0.008	1E-09	direct contact	aquatic biota
Surface Impoundments				
Boron	2000	4	direct contact	aquatic biota
Lead	20	0.02	ingestion	river otter
Arsenic	10	0.01	direct contact	aquatic biota
Selenium	10	0.02	direct contact	aquatic biota
Cobalt	5	0.007	direct contact	aquatic biota
Barium	2	0.003	direct contact	aquatic biota
Cadmium	1	0.004	direct contact	aquatic biota
Aluminum	0.02	0.0003	direct contact	aquatic biota

[a] Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

4.2.2 Sediment Receptors

Table 4-15 presents the 90th and 50th percentile results of the ground-water-to-surface-water pathway for sediment receptors for landfills and surface impoundments. For landfills, lead, (20), arsenic (6), and cadmium (2) show 90th percentile risks above the risk criteria. For surface impoundments, lead (200), arsenic (100), and cadmium (20) showed 90th percentile risks above the risk criteria. Although cadmium was not above the risk criterion in surface water, it did have an HQ of 20 in sediments at the 90th percentile. None of the constituents modeled showed sediment risks at or above the risk criteria at the 50th percentile.

Table 4-15. Summary of Full-Scale CCW Ecological Risk Results: Groundwater-to-Surface-Water Pathway, Sediment Receptors[a]

Chemical	90th Percentile HQ	50th Percentile HQ	Pathway	Receptor
Landfills				
Lead	20	3E-08	ingestion	spotted sandpiper
Arsenic	6	7E-04	ingestion	spotted sandpiper
Cadmium	2	6E-05	direct contact	sediment biota
Antimony	0.9	4E-05	direct contact	sediment biota
Molybdenum	0.05	1E-05	ingestion	spotted sandpiper
Barium	0.002	6E-21	ingestion	spotted sandpiper
Surface Impoundments				
Lead	200	0.05	ingestion	spotted sandpiper
Arsenic	100	0.2	ingestion	spotted sandpiper
Cadmium	20	0.009	direct contact	sediment biota
Molybdenum	0.7	0.002	ingestion	spotted sandpiper
Barium	0.007	8E-06	ingestion	spotted sandpiper

[a] Zero results indicate that contaminant infiltration rates were too small for the contaminant plume to reach the receptor during the 10,000 year period of the analysis.

4.2.3 Constituents Not Modeled in the Full-Scale Assessment

As described in Section 2.1.1.2, resources did not allow full-scale modeling to be conducted for 6 constituents with generally lower risks to ecological receptors.[9] These chemicals (chromium, vanadium, beryllium, copper, silver, and zinc), had surface water pathway HQs in the screening analysis ranging from 16 to 110 for landfills, and four (chromium, vanadium, copper, and silver) had screening HQs ranging from 14 to 33 for surface impoundments.

These constituents were addressed using risk attenuation factors developed by dividing the screening risk results by the full-scale risk results for the constituents modeled in the full-scale assessment. Tables 4-16 and 4-17 show the results of this comparison for the surface water ecological risk exposure pathway. Table 4-16 shows the risk attenuation factors for the modeled constituents, and Table 4-17 shows the results of applying the median (central tendency) and 10th percentile (conservative) attenuation factors to the screening risk results for constituents that were not modeled.

For landfills, the risk attenuation factors ranged from 50 to 2,000. Both the median and 10th percentile risk attenuation factors were adequate to reduce risks to an HQ below 1 for all constituents except for silver. Although silver shows an HQ of 1.5 using the 10th percentile

[9] These constituents had only one or no ecological HQs greater than 100.

attenuation factor, silver's low mobility would probably result in a higher attenuation factor (i.e., at the median or greater).

For surface impoundments, risk attenuation factors ranged from 7 to 64, reflecting higher contaminant mobility from the higher hydraulic head in the surface impoundments and a lower prevalence of liners (compared to landfills). HQs were reduced below 1 for all four unmodeled constituents with the median attenuation factor (38), and the HQ for silver was reduced to 0.8 by applying the 10th percentile attenuation factor (17). The other three constituents (chromium, vanadium, and copper) show risks only slightly above the risk criteria with the10th percentile attenuation (HQs ranging from 1.4 to 1.9). It is unlikely that these results represent true risks above the risk criteria: vanadium and copper are likely less mobile than the 10th percentile attenuation factor reflects (thus the true risk is likely lower), and the risks for chromium are based on the highly conservative assumption of 100 percent hexavalent chromium.

Table 4-16. Risk Attenuation Factor[a] Statistics for Modeled Constituents—Ecological Risk, Surface Water Pathway

Statistic	Landfill	Surface Impoundment
10th percentile	75	17
50th percentile	178	38
Average	483	38
Maximum	2,000	64
Number of data points	6	7

[a] The risk attenuation factor is the ratio of the full-scale analysis risk and screening analysis risk for a constituent modeled in the full-scale analysis.

Table 4-17. Summary of Risk Results Using Risk Attenuation Factors—Ecological Risk, Surface Water Pathway

WMU/Pathway	Landfill			Surface Impoundment		
	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation	Screening HQ	HQ with Median Attenuation	HQ with 10th Percentile Attenuation
Chromium VI	18	0.1	0.2	33	0.9	1.9
Vanadium	23	0.1	0.3	24	0.6	1.4
Beryllium	24	0.1	0.3	-	-	-
Copper	16	0.09	0.2	31	0.8	1.8
Silver	110	0.6	1.5	14	0.4	0.8
Zinc	16	0.09	0.2	-	-	-

4.3 Sensitivity Analysis

EPA conducted a sensitivity analysis on the probabilistic risk assessment to determine which model inputs were most important to risk, which in turn will help focus additional analyses or data collection efforts on the most important drivers of risk, and help identify the important factors to consider when evaluating regulatory and management options for CCW. The sensitivity analysis also can help identify parameters that are both sensitive and highly uncertain, which affects the confidence in the results. This sensitivity analysis used a response-surface regression method that derives a statistical model for risk (as the dependent variable) based on the input parameters from the probabilistic analysis (as independent variables).

Environmental concentration (rather than risk) was chosen as the dependent variable for the sensitivity analysis because (1) there is a direct, linear relationship between environmental concentrations and risks and (2) the additional inputs used to calculate risk from environmental concentration (i.e., exposure factors, such as body weight, ingestion rates) are lifestyle variables that are not amenable to regulation to reduce or manage risk. Furthermore, these variables have well-established, peer-reviewed, national distributions, which are regularly used in the probabilistic national risk analyses conducted by EPA. Therefore, the contribution of the exposure factors to the variability in risk is not particularly useful for the purposes of the sensitivity analysis: to help direct additional analyses in support of developing CCW regulatory options, to help focus any future data collection efforts on the most sensitive variables, or to better understand sources of uncertainty in the CCW risk results.

The outputs from the sensitivity analysis are the goodness-of-fit values for the regression models and the relative importance of each input parameter in determining environmental concentrations across different WMU, waste type, and constituent scenarios. The goodness-of-fit values of the regression models were moderate to very good for the drinking water pathway (R^2=0.53–0.90) and good to very good for fish consumption (R^2=0.76–0.90). In general, the drinking water pathway had a larger number of input parameters that were significant (seven) than the fish consumption pathway (three). The most sensitive parameters for most (over 75 percent) of the drinking water scenarios[10] evaluated were parameters impacting groundwater flow:

- Infiltration rate within the WMU footprint
- Leachate concentration from the WMU
- Aquifer hydraulic conductivity and gradient (i.e., groundwater velocity).

For strongly sorbing contaminants (i.e., metals with high soil/water partition coefficients), sorption and travel time parameters become more important, including

- Adsorption isotherm coefficient
- Depth to groundwater
- Receptor well distance.

[10] Scenarios represent unique combinations of WMU, waste type, chemical, exposure pathway, and receptor.

For the fish consumption pathway, only three variables were consistently significant across scenarios:

- Infiltration rate within the WMU footprint
- Leachate concentration from the WMU
- Waterbody flow rate.

Additional detail on how the CCW sensitivity analysis was conducted can be found in U.S. EPA (2005). In terms of the model inputs, the sensitivity analysis found that the most consistent drivers of the risk results are constituent concentration in waste leachate (i.e., the source term for the risk assessment and infiltration rate through the WMU), which is largely controlled by the liner conditions and, to a lesser extent, soil type and (for landfills only) precipitation. These variables and their uncertainties are discussed in the following section.

4.4 Variability and Uncertainty

Variability arises from true heterogeneity in characteristics, such as body weight differences within a population or differences in contaminant levels in the environment.

Uncertainty represents a lack of knowledge about factors such as the nature of adverse effects from exposure to constituents, which may be reduced with additional research to improve data or models.

Variability and uncertainty are different conceptually in their relevance to a probabilistic risk assessment. Variability represents true heterogeneity in characteristics, such as body weight differences within a population or differences in pollutant levels in the environment. It accounts for the distribution of risk within the exposed population. Although variability may be known with great certainty (e.g., age distribution of a population may be known and represented by the mean age and its standard deviation), it cannot be eliminated and needs to be treated explicitly in the assessment. Uncertainty is a description of the imperfection in knowledge of the true value of a particular parameter. In contrast to variability, uncertainty can be reduced through additional information-gathering or analysis (i.e., better data, better models). EPA typically classifies the major areas of uncertainty in risk assessments as scenario uncertainty, model uncertainty, and parameter uncertainty. Scenario uncertainty refers to missing or incomplete information needed to fully define exposure and dose. Model uncertainty is a measure of how well the model simulates reality. Parameter uncertainty is the lack of knowledge regarding the true value of a parameter used in the assessment.

Uncertainty and variability can be addressed two ways:

- By varying parameter values in a probabilistic assessment such as a Monte Carlo analysis
- By comparing the data or results to other data or other studies such as damage cases or alternative results based on different assumptions.

In planning this assessment, we addressed as much of the variability as possible, either directly in the Monte Carlo analysis or through aggregation of the data into discrete elements of the analysis. For example, spatial variability in soil, aquifer, and climate data is accounted for by using distributions for soil and aquifer properties around the facility when the actual

environmental characteristics around a WMU are uncertain. Conversely, variability in waste leachate concentrations was represented by a national database of CCW constituent concentrations from disposal sites around the country. These data were aggregated by waste and WMU types that were defined by statistically significant differences in concentration. Variability in human exposure factors (e.g., body weight, ingestion rates) was accounted for using national distributions that represent the range of possible values.

Because CCW is generated nationwide, its disposal may occur anywhere in the United States. Thus, this assessment characterized environmental conditions that influence the fate and transport of constituents in the environment using site-specific data collected around coal-fired power plants with onsite CCW disposal facilities. Spatial variability in environmental setting was accounted for by the site-to-site variables for the 181 CCW disposal sites modeled in the analysis using 41 different climate regions and 9 different resources regions throughout the contiguous 48 states.

In summary, a distribution of exposures was developed that includes specific consideration of the variability in the following sensitive model parameters

- WMU characteristics, in particular liner type (which strongly influences infiltration rate)
- CCW constituent concentrations in waste leachate
- Distance to nearest well
- Site-specific environmental conditions (especially groundwater flow conditions)
- Human exposure factors.

Uncertainty also was considered in the analysis by using reasonable ranges and distributions when variables were not known exactly. For example, when a soil texture or groundwater flow conditions could not be precisely assigned at a site, multiple soil types or hydrogeologic environments would be sampled based on the soil and aquifer types that are likely to be present at the site.

The treatment of variability and uncertainty in model parameters using a Monte Carlo simulation forms the basis for the national exposure distributions used in this analysis to estimate risk. Previous sections of this document describe how we generated distributions and estimated input parameter values and then used these values in models to estimate risk. The discussion in this section focuses on how this treatment of variability and uncertainty affects the analysis results and on various comparisons we performed on the results or critical input data to evaluate uncertainty.

4.4.1 Scenario Uncertainty

Sources of scenario uncertainty include the assumptions and modeling decisions that are made to represent an exposure scenario. Because this risk assessment attempts to characterize current conditions by estimating risks from actual CCW disposal sites across the country, it is subject to less scenario uncertainty than risk assessments that rely on hypothetical conceptual models. However, certain aspects of the scenario are uncertain.

CCW Management Unit Data. The landfills and surface impoundments modeled in this risk assessment were placed, sized, and lined according to data from the 1995 EPRI survey (EPRI, 1997). New data collected by EPA and DOE since this risk assessment was conducted (U.S. DOE, 2006) indicate that liners are much more prevalent in WMUs constructed or expanded from 1994 through 2004 than in units in place before that. This suggests that the risks may be lower for future CCW disposal facilities (although most of the unlined WMUs have been closed with wastes remaining in the units).

Liner-related questions are especially important because liner configurations greatly influence infiltration rates, one of the most sensitive parameters in the risk assessment. In terms of risks through groundwater pathways, this risk assessment has shown that liners, in particular composite (combined clay and synthetic) liners, can limit risks through subsurface exposure pathway, and the DOE/EPA survey shows that liners are more prevalent in newly constructed WMUs and WMU expansions. Although the DOE/EPA survey does not shed light on how many unlined facilities are still operating today, it does indicate that more units are lined today than were in the 1995 EPRI survey data set on which this risk assessment is based.

Receptor Populations Evaluated. The human receptors evaluated for the CCW risk analysis are a family with children residing near the CCW disposal facility, drinking from a private well screened in a surficial aquifer or eating fish caught from a nearby stream or lake impacted by CCW leachate. Additionally, except for a 15-day vacation, it is assumed that adults and children are exposed daily and that the private well is the only source of drinking water. Although it is possible for other types of individuals to be exposed, the use of the resident adult and child as protective of other receptors and pathways is a conservative, simplifying assumption of the analysis. The lack of information to define and model actual exposure conditions also introduces uncertainty into this assessment, but EPA believes that the national distribution of exposure factors used is appropriate for a national assessment.

Additive Risks Across Pathways. The human receptors evaluated in the CCW risk assessment are assumed not to consume both contaminated fish and drinking water. Although this could potentially miss some higher exposures for a maximally exposed individual, analysis of the individual pathway results does not indicate that adding such risks would significantly change the conclusions of this risk assessment in terms of the constituents and exceeding the risk criteria.

Co-Occurrence of Ecological Receptors and Constituents. As a simplification for national-scale analyses in the absence of site-based data, co-occurrence of the ecological receptors and the constituents of concern is typically assumed. However, the prior probability that a receptor will be found in waterbodies affected by constituent releases from CCW WMUs is not known, nor is it known whether a receptor will forage for food in contaminated areas or if those areas do, in fact, support the type of habitat needed by the receptor. Although the assumption of co-occurrence was necessary for this analysis, relatively few field studies are available to demonstrate the relationship between adverse ecological effects and constituent releases from CCW as it is currently managed.

Ecosystems and Receptors at Risk. One of the most intractable problems in conducting a predictive ecological risk assessment intended to reflect risks at a national scale is evaluating *all* of the receptors and ecosystems at risk. In *Wastes from the Combustion of Coal by Electric Utility Power Plants - Report to Congress* (U.S. EPA, 1988b), the authors pointed out that plants or animals of concern were located within a 5-km radius of the CCW WMUs at 12 to 32 percent of the sites. Although these figures are of limited spatial resolution, they suggest the possibility that threatened and endangered species or critical habitats may be at risk from CCW constituents. Examples of other critical assessment endpoints not evaluated in this analysis include the following:

- **Managed Lands:** Because ecosystem degradation is proceeding at an unprecedented rate, and because protected lands play a critical role in preserving plant and animal species, managed areas in the United States represent well-recognized ecological values. Managed lands refer to a variety of lands designated by the federal government as worthy of protection, including National Wildlife Refuges, National Forests, Wilderness areas, and National Recreation areas.
- **Critical Habitats:** Although critical habitats may be defined in a number of ways (e.g., presence of threatened species, decreasing habitat area), wetlands are widely recognized as serving critical ecological functions (e.g., maintenance of water quality). The U.S. Fish and Wildlife Service estimates that approximately 45 percent of the Nation's threatened and endangered species directly depend on aquatic and wetland habitats. Consequently, impacts of chemical stressors on wetland habitats may have high ecological (and societal) significance. The presence of critical habitats such as wetlands is also used to inform the selection of ecological receptors (e.g., amphibians, waterfowl) and the construction of appropriate food webs.
- **Threatened and Endangered Species:** For most ecological risk assessments of chemical stressors, available data on toxicity and biological uptake are sufficient to support the evaluation of effects on representative species populations or generalized communities (e.g., aquatic community). However, despite their obvious value, threatened and endangered species are frequently excluded from the analytical framework for national rulemakings. The assessment of threatened and endangered species requires a site-based approach in which locations, habitats, and species of concern are identified and characterized with respect to the spatial scale of constituent releases.

4.4.2 Model Uncertainty

Model uncertainty is associated with all models used in a risk assessment because models and their mathematical expressions are simplifications of reality that are used to approximate real-world conditions and processes and their relationships. Computer models are simplifications of reality, requiring exclusion of some variables that influence predictions but that cannot be included in models either because of their complexity or because data are lacking on a particular parameter. Models do not include all parameters or equations necessary to express reality because of the inherent complexity of the natural environment and the lack of sufficient data to describe the natural environment. Because this is a probabilistic assessment that predicts what may occur with the management of CCW under actual scenarios, it is possible to compare the results of these models to specific situations.

The risk assessor needs to consider the importance of excluded variables on a case-by-case basis because a given variable may be important in some instances and not important in others. A similar problem can occur when a model that is applicable under one set of conditions is used for a different set of conditions. In addition, in some instances, choosing the correct model form is difficult when conflicting theories seem to explain a phenomenon equally well. In other instances, EPA does not have established model forms from which to choose to address certain phenomena, such as facilitated groundwater transport.

Models used in this analysis were selected based on science, policy, and professional judgment. These models were selected because they provide the information needed for this assessment and because they are generally considered to reflect the state of the science. Even though the models used in this analysis are used widely and have been accepted for numerous applications, they each retain significant sources of uncertainty. These limitations are well documented in the model development references cited in Section 3.

Although the sources of model uncertainty in this assessment could result in either an overestimation or an underestimation of risk, the models employed in this assessment have been developed over many years to support regulatory applications. As a result they have been designed to be protective towards the impacted populations that they represent. In other words, where simplifying assumptions are necessary, the assumptions are made in a way that will not underestimate risk.

Arsenic Speciation. Because the models used in this assessment do not speciate metals during soil or groundwater transport, arsenic speciation in the subsurface is a significant groundwater modeling uncertainty in this analysis. Arsenic can occur in either a +3 (arsenic III) or +5 (arsenic V) oxidation state in groundwater, with arsenic III being the more mobile form. Because the soil and groundwater models assume one form for each model run, the risk results presented for arsenic are based on arsenic III, which is a conservative, protective assumption (i.e., arsenic III has higher risks than arsenic V). Although arsenic is generally thought to occur in the +3 form in leachate, there is evidence from damage cases at CCW disposal sites that suggests that arsenic III is rapidly converted to arsenic V during subsurface transport, with the result that drinking water standards are rarely exceeded in offsite groundwater in spite of high landfill leachate concentrations (see, for example, U.S. EPA, 2000; U.S. EPA, 2003e; Lang and Schlictmann, 2004; Zillmer and Fauble, 2004). To address this uncertainty (i.e., how much an arsenic III assumption might overpredict offsite well concentrations) the models were run assuming arsenic V as the arsenic species in soil and groundwater. Figure 4-4 compares the risk results for arsenic III and arsenic V. Arsenic V has lower risks than arsenic III by about a factor of two, but the 90th percentile risks are still above risk criteria.

Bioavailability of Constituents to Ecological Receptors. For the purposes of this analysis, the model assumes that all forms of a constituent are equally bioavailable to ecological receptors, and therefore, the actual exposures that may occur in the field tend to be overestimated, thus making this a protective assumption. Both the chemical form and the environmental conditions influence bioavailability and ultimately the expression of adverse effects. For example, as discussed above, the form of arsenic has been shown to profoundly influence mobility and toxicity.

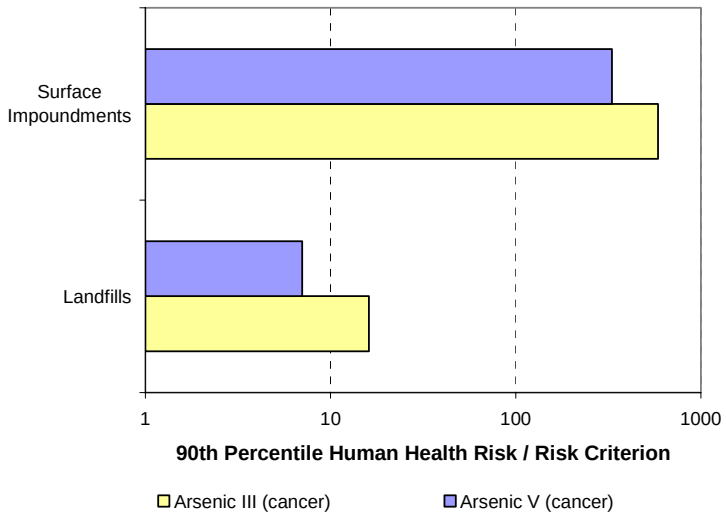


Figure 4-4. Comparison of risk results for arsenic III and arsenic V (based on results for all units combined).

Multiple Constituent Exposures to Receptors. The risk from each constituent was considered separately in this analysis. However, the waste concentration data on CCWs (as well as recent field studies such as U.S. EPA, 2006) suggest that exposure to multiple constituents is highly likely. The synergism or antagonism between different constituent combinations may elicit unexpected adverse impacts to humans and ecosystems. Hence, a single-constituent analysis may underestimate risks associated with multiple chemical stressors.

4.4.3 Parameter Uncertainty and Variability

Parameter uncertainty occurs when (1) there is a lack of data about the values used in the equations, (2) the data that are available are not representative of the particular instance being modeled, or (3) parameter values have not been measured precisely or accurately because of limitations in measurement technology. Random, or sample, errors are a common source of parameter uncertainty that is especially critical for small sample sizes, as illustrated by the FBC waste results discussed in Section 4.1.3.2. More difficult to recognize and address are nonrandom or systematic errors that can bias the analyses from sampling errors, faulty experimental designs, or bad assumptions.

Spatial and temporal variability in parameters used to model exposure account for the distribution in the exposed population. For example, the rainfall or precipitation rates used to calculate infiltration and recharge to groundwater are measured daily by the National Weather Service at many locations throughout the United States, and statistics about these parameters are well documented. Although the distributions of these parameters may be well known, their actual values vary spatially and temporally and cannot be predicted exactly. Thus, the annual average infiltration rates used in the source model for a particular climate station will provide information on average conditions appropriate for this analysis. Additionally, using data from multiple climate stations located throughout the United States can account for some, but not all, spatial variability.

4.4.3.1 Waste Concentrations

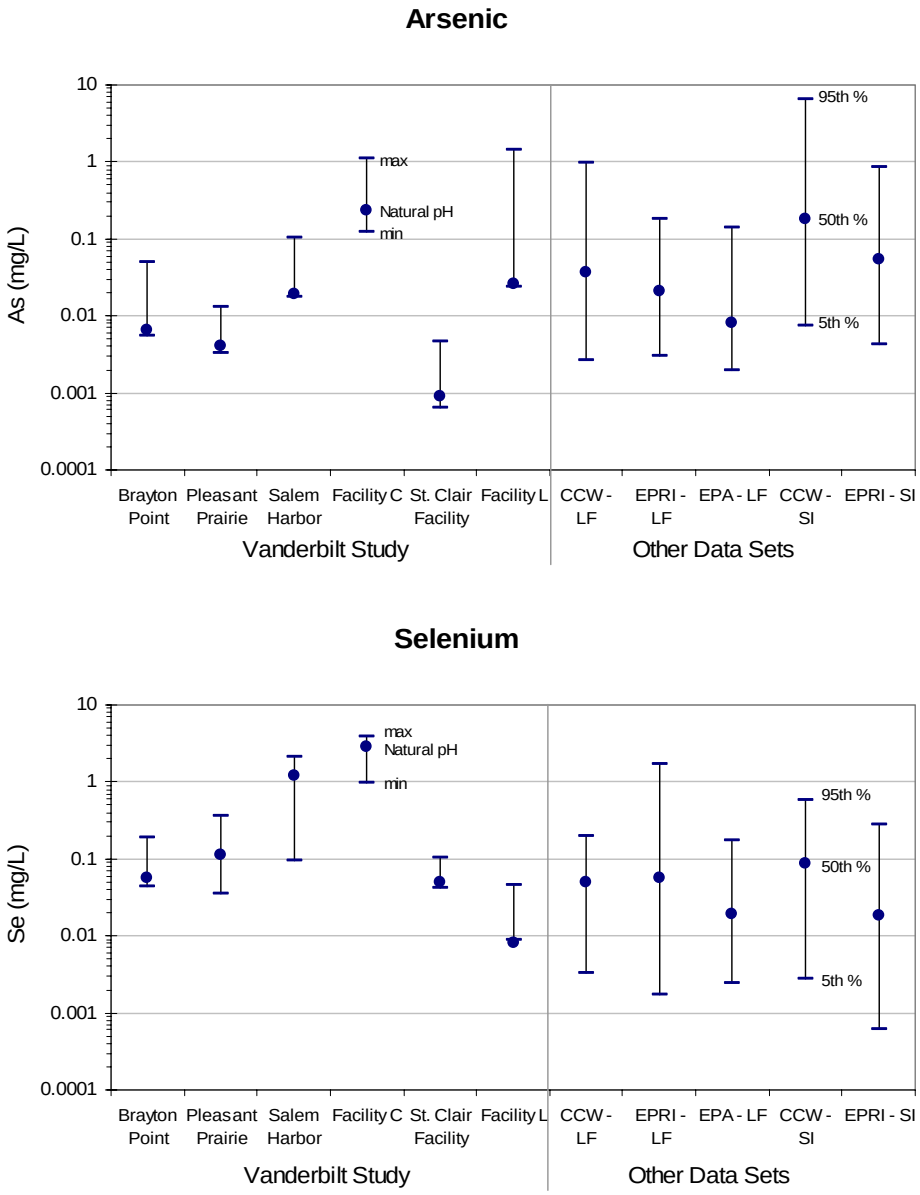
The CCW constituent database used to represent CCW total waste and waste leachate concentrations is arguably the most important data set in terms of driving the risk assessment results. The constituent data are subject to two primary uncertainties beyond the normal sampling and analysis uncertainty associated with environmental measurements: (1) the appropriateness of the landfill leachate data used in the analysis and (2) high percentages of nondetect analyses for some CCW constituents.

Appropriateness of Leachate Data. The CCW leachate data were collected from a varying number of sites using a variety of methods. The available landfill data are largely derived from the TCLP, a laboratory test designed to estimate leachate concentrations in municipal solid waste (MSW) landfills. The TCLP has been shown to both over and underpredict leachate concentrations for other waste disposal scenarios, so the use of the TCLP data to represent CCW leachate is another source of uncertainty. However, as noted below, this does not appear to be a significant source of uncertainty for this analysis.

Surface impoundment leachate is represented by porewater data taken beneath actual impoundments, but although these data arguably should better represent leachate concentrations, they are fewer in number than the landfill data and therefore subject to uncertainty as to how representative they are of all CCW wastes. Antimony, cobalt, mercury, and thallium are represented by one to only a few sites and only a few measurements, and results associated with these metals should be interpreted with caution. Results for surface impoundments for antimony, mercury, and thallium are not presented due to the paucity of leachate data (1 or 2 sites, and 11 or fewer values).

Since the CCW risk assessment was been conducted in 2003, EPA-sponsored research conducted by Vanderbilt University has improved the scientific understanding of the generation of leachate from CCW, in particular for mercury, arsenic, and selenium (U.S. EPA, 2006). Figure 4-5 plots the results from this study for arsenic and selenium, along with data from EPA's Leach2000 database and EPRI (as provided in U.S. EPA, 2006), against the data used for landfills and surface impoundments used in the CCW analysis. For the Vanderbilt leaching study, data are provided for each ash tested, with the minimum, maximum, and value at natural pH plotted on the chart. Percentile values (95th, 50th, 5th) are plotted for the compiled data sets (EPA, EPRI, and CCW), and mercury is not modeled for landfills because of a high number of nondetects.

For arsenic, the CCW values bracket the range found in the other studies. Selenium values also agree fairly well for CCW landfill data, although the CCW landfill values appear to be lower than some of the values from the other studies, suggesting that selenium risks may be somewhat underestimated for landfills in this analysis. This is significant even though selenium risks from landfills were not above the risk criteria in this analysis, because selenium is often reported as a constituent of concern (along with arsenic and boron) in CCW damage cases (U.S. EPA, 2000; U.S. EPA, 2003e; Lang and Schlictmann, 2004; Zillmer and Fauble, 2004).



Key to data sets:

Vanderbilt	=	U.S. EPA (2006)
CCW	=	CCW Constituent Database (this analysis)
EPRI	=	EPRI Leachate data (from U.S. EPA, 2006)
EPA	=	Leach 2000 data (from U.S. EPA, 2000)
LF	=	landfills
SI	=	surface impoundments

Figure 4-5. Comparison of CCW leachate data with other leachate data.

Although the Vanderbilt Study does not cover all of the metals addressed in the CCW analysis, its general agreement with the CCW arsenic and selenium levels does help allay concerns that the TCLP CCW leachate values used in the analysis markedly overestimate or underestimate the concentrations actual CCW leachate.

Mercury and Nondetect Analyses. For certain of the CCW constituents addressed in this analysis, the CCW leachate database contains a large number of nondetect measurements (concentrations below an analytical instrument's ability to measure). Table 4-18 illustrates this point by showing, by WMU type and chemical, the overall percent of nondetect values for each chemical and the percent of site-averaged values[11] that are composed entirely of nondetect measurements. Constituents that could not be addressed in this analysis because of a high number of nondetects include mercury (for landfills and surface impoundments) and thallium, antimony, and cobalt (for surface impoundments only). Mercury is of particular interest because it is the only constituent with significant concern through the fish consumption pathway, and because there is the potential for mercury concentrations in CCW to increase as flue gas mercury controls are installed on coal-fired power plants in response to the Clean Air Interstate Rule (CAIR) and the Clean Air Mercury Rule (CAMR).

Recent work by Vanderbilt University (U.S. EPA, 2006) sheds some light on mercury concentrations in leachate from some CCWs. Figure 4-6 plots the CCW distribution of mercury concentrations (assuming half the detection limit for mercury values below detection) against results from the Vanderbilt work and recent data collected by EPRI (U.S. EPA, 2006). Assuming half the detection limit, the CCW mercury leachate values are about an order of magnitude or more higher than the Vanderbilt or EPRI data. With a single CCW leachate analysis available for surface impoundments, it is difficult to draw firm conclusions, but the concentration value, which corresponds to a 90th percentile HQ of 20, is above the maximum value shown in the other studies. In short, the mercury levels in the CCW database are not useful because of high detection limits. In addition, the Vanderbilt study found that older mercury analyses, like the ones in the CCW database, could be biased high because of cross-contamination issues.

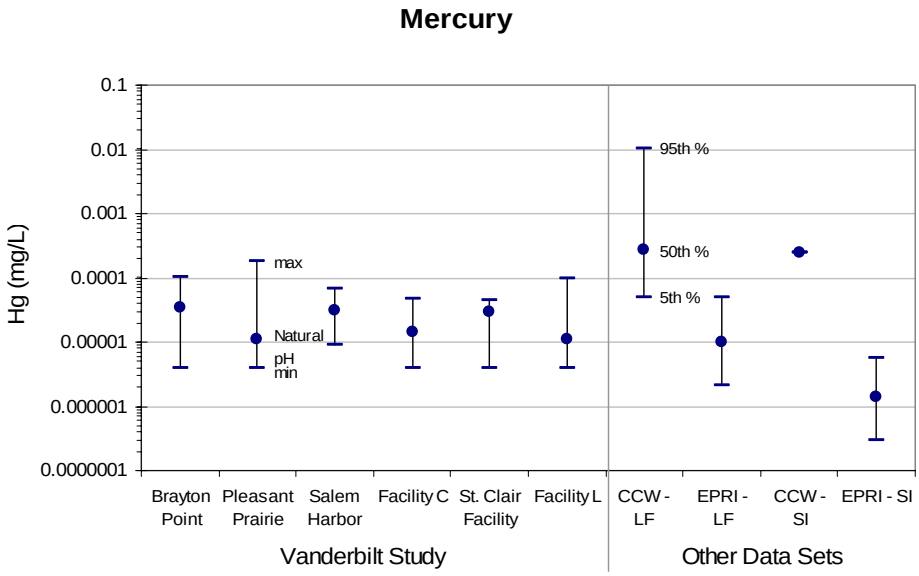
Finally, U.S. EPA (2006) and preliminary results of ongoing EPA studies suggest that both mercury levels and mercury leachability in CCW can vary depending on the flue gas mercury controls used at a power plant. Additional work is underway in this area.

[11] As explained in Appendix A, the CCW risk assessment uses site-averaged constituent concentrations. That is, an average value was used when there were multiple measurements for a chemical at a particular site.

Table 4-18. Proportion of Nondetect Analyses for Modeled CCW Constituents

Chemical	Measurements		Sites	
	Number	% nondetects	Number	% with all nondetects
Landfills				
Aluminum	397	18%	61	5%
Antimony	496	50%	66	41%
Arsenic	1182	49%	128	20%
Barium	1225	11%	126	5%
Boron	930	8%	83	2%
Cadmium	1237	50%	124	31%
Cobalt	559	56%	52	19%
Lead	1109	60%	125	30%
Mercury	***974***	***91%***	***101***	***58%***
Molybdenum	373	24%	58	10%
Nitrate/Nitrite	141	48%	20	15%
Selenium	1227	49%	131	17%
Thallium	402	60%	40	45%
Surface Impoundments				
Aluminum	158	10%	16	6%
Antimony	***11***	***100%***	***2***	***100%***
Arsenic	155	16%	16	6%
Barium	161	14%	16	13%
Boron	164	7%	171	6%
Cadmium	164	68%	16	50%
Cobalt	49	59%	4	50%
Lead	138	78%	14	36%
Mercury	***1***	***100%***	***1***	***100%***
Molybdenum	161	37%	17	24%
Nitrate/Nitrite	267	59%	14	7%
Selenium	140	33%	15	20%
Thallium	***11***	***100%***	***2***	***100%***

Results for constituents shown in ***bold italics*** were not presented in this report because of high detection limits or limited data.



Key to data sets:

Vanderbilt	=	U.S. EPA (2006)
CCW	=	CC Constituent Database (this analysis)
EPRI	=	EPRI Leachate data (from U.S. EPA, 2006)
EPA	=	Leach 2000 data (from U.S. EPA, 2000)
LF	=	landfills
SI	=	surface impoundments

Figure 4-6. CCW mercury concentrations compared with other leachate data.

4.4.3.2 WMU Locations and Characteristics

The locations of the specific sites in the United States where CCW is disposed are known, and EPA used the soil and climatic characteristics of these sites in the Monte Carlo analysis. Because most locations were facility front gates or centroids, the exact location of the CCW landfill or surface impoundment was not known. To account for this uncertainty, soil data were collected for an area around the plant and soil type distributions were sampled in the Monte Carlo analysis. Climate center assignments were combined with the soil texture distributions to select infiltration and recharge rates to use in the analysis.

WMU area, depth, volume, and liner type were not varied in the Monte Carlo analysis because values for these variables were known from the EPRI survey data. More uncertain parameters, like depth below grade, were varied within reasonable ranges. These data were used in the source model calculations to generate the distribution of environmental releases used by the fate and transport modeling.

Three standard WMU liner scenarios (clay, composite, and unlined) were assigned to each facility based on best matches to data in the EPRI survey on liner type. Infiltration through these liners was then modeled using assumptions, models, and data developed in support of EPA's Industrial Subtitle D guidance. How well these assumptions and models represent the

performance of CCW WMU landfills and surface impoundments is an uncertainty in this analysis.

4.4.3.3 Fate and Transport Model Variables

The parameter values required to model contaminant fate and transport in groundwater were obtained from site-specific, regional, and national databases. Hydrogeologic environment was assigned to each site, based on geologic maps and soil conditions; where assignments were uncertain, two or three settings might be used in the Monte Carlo analysis. Because aquifer properties are highly variable and uncertain, reasonable sets of aquifer properties were selected, based on hydrogeologic environment, from a hydrogeologic database.

Receptor Location (Drinking Water Wells). The sensitivity analysis (Section 4.3) showed that distance of a receptor from the contaminant source is an important influence on media concentration, especially for contaminants that strongly sorb to soil and aquifer materials. For the groundwater-to-drinking-water pathway, receptor location was represented as the distance and position, relative to a contaminant plume, of residential drinking water wells from the WMU. Because no data were readily available on the distance of CCW disposal sites from residential wells, EPA used data from a survey of well distances from MSW landfills. Whether or not this is an accurate representation of well distance for CCW landfills and surface impoundment is one of the larger uncertainties in this analysis. EPA believes that the MSW well distance distribution used is protective for CCW landfills and surface impoundments.

Location and Characteristics of Waterbodies. One aspect of the site configuration of particular relevance to the aquatic food chain modeling is the locations and characteristics of the waterbodies. The size of the waterbodies (and the distance from the WMU) affects constituent concentrations and loadings predicted for that waterbody. The location of the waterbody was based on an empirical distribution of measurements, taken from actual CCW sites, of the distance from the edge of the WMU to the nearest stream or lake. The uncertainty posed in this analysis is the sampling of this distribution as compared to a more certain measurement of the actual distance at each CCW site. Surface water variables, including flow and water quality parameters, were collected for the stream reach being modeled, or for a larger hydrologic region where data were not available for a particular reach.

Environmental Parameters. Uncertainties related to environmental parameters (soil, aquifer, surface water, climate data) have already been mentioned. The parameters with the largest impact on results are aquifer hydraulic conductivity and gradient, which are selected from a national database of aquifer properties.

Fish Bioconcentration and Bioaccumulation Factors. For fish consumption, exposure dose is calculated using BCFs to estimate the transfer of pollutants from environmental media into fish. Uncertainty is associated with models used to estimate BCFs for aquatic biota. The aquatic BCFs were developed based on total surface water concentrations and concentrations in aquatic biota.

4.4.3.4 Exposure and Risk Modeling Variables

Exposure parameters and benchmarks for human and ecological risk also contribute to parameter variability and uncertainty.

Human Exposure Factors. Individual physical characteristics, activities, and behavior are quite different, and thus the exposure factors that influence the exposure of an individual, including ingestion rate, body weight, and exposure duration, are quite variable. Exposure modeling relies heavily on default assumptions concerning population activity patterns, mobility, dietary habits, body weights, and other factors. The probabilistic assessment for the adult and child exposure scenario addressed the possible variability in the exposure modeling by using statistical distributions for these variables for each receptor in the assessment: adult and child resident and adult and child recreational fisher. Data on fish consumption rates are not available for children; thus the adult data were used for children in this analysis, which could overestimate risk from this pathway for children. For all exposure factors varied, a single exposure factor distribution was used for adults for both males and females. For child exposures, one age (age 1) was used to represent the age at the start of exposure, because this age group is considered to be most sensitive for most health effects.

The *Exposure Factors Handbook* (U.S. EPA, 1997c,d,e) provides the current state of the science concerning exposure assumptions, and it was used throughout this assessment to establish statistical distributions of values for each exposure parameter for each receptor. There are some uncertainties, however, in the data that were used. Although it is possible to study various populations to determine various exposure parameters (e.g., age-specific soil ingestion rates or intake rates for food) or to assess past exposures (epidemiological studies) or current exposures, risk assessment is about prediction. Therefore, long-term exposure monitoring in this context is infeasible.

Diet Assumptions for Ecological Receptors. National-scale assessments often assume maximum intake of contaminated prey in the diets of primary and secondary consumers (i.e., 100 percent of the diet originates from the contaminated area). Under field conditions, many receptors are opportunistic feeders with substantial variability in both the type of food items consumed as well as the geospatial patterns of feeding and foraging. The actual proportion of wildlife receptors' diets that would be contaminated depends on a number of factors such as the species' foraging range, quality of food source, season, intra- and interspecies competition. Consequently, the exclusive diet of contaminated food items tends to provide a very conservative estimate of potential risks.

Human Health Benchmarks. EPA routinely accounts for uncertainty in its development of RfDs and other human health benchmarks. For example, if certain toxicological data are missing from the overall toxicological database (e.g., reproductive data), EPA accounts for this by applying an uncertainty factor. In general, EPA human health benchmarks are derived using a health-protective approach.

Ecological Criteria. CSCLs were developed for constituents when sufficient data were available. In many cases, sufficient data were unavailable for a receptor/constituent combination, and therefore, the potential risk to a receptor could not be assessed. In particular, insufficient

data were available to derive chronic effects CSCLs for amphibians. Because the risk results can only be interpreted within the context of available data, the absence of data can not be construed to mean that adverse ecological effects will not occur.

In addition to the effects of data gaps on ecological benchmarks, the ecological criteria tend to be fairly conservative because the overall approach is based on "no effects" or "lowest effects" study data. In site-specific assessments, a *de minimis* effects approach is often replaced with an effects level similar to natural population variability (e.g., sometimes as high as a 20 percent effects level). As a result, the CSCLs used in this analysis are likely to overestimate risks for representative species and communities assumed to live in surface waters impacted by CCW WMUs. Because the difference between a lowest observed adverse effect level (LOAEL) and a NOAEL is often about a factor of 10, an HQ exceedance of roughly 10 may not be ecologically significant. In contrast, CSCLs based on no effects data that are developed for the protection of threatened and endangered species are presumed to be protective.

4.5 Summary and Conclusions

One of the most sensitive parameters in the risk assessment is infiltration rate. Infiltration rate is greatly influenced by whether and how a WMU is lined. The 1994 to 2004 DOE/EPA survey results (U.S. DOE, 2006) do not include how many unlined facilities are still operating today, but do indicate that more facilities are lined today than were in the 1995 EPRI survey data set on which this risk assessment is based. This suggests that the risks from future CCW disposal facilities are likely to be lower than the results presented in this report. EPA will continue to work to integrate the DOE/EPA survey data into the CCW risk assessment and is seeking comments on how to address data gaps, in particular: (1) how to estimate the overall prevalence of liners in the CCW disposal facilities today, (2) how to determine the area and capacity of newer CCW landfills and surface impoundments, and (3) how the liners currently in CCW WMUs perform when compared to the industrial liner conditions assumed in this risk assessment.

Composite liners, as modeled in this risk assessment, effectively reduce risks from all pathways and constituents below the risk criteria for both landfills and surface impoundments.[12] The CCW risk assessment suggests that the management of CCW in unlined landfills and unlined surface impoundments may present risks to human health and the environment. Risks from clay-lined units, as modeled, are about one-third to one-half the risks of unlined units, but are still above the risk criteria used for this analysis. These risk results are largely consistent with damage cases compiled by EPA (U.S. EPA, 2000, 2003e, 2007) and others (Lang and Schlictmann, 2004; Zillmer and Fauble, 2004; Carlson and Adriano, 1993). Key risk findings include the following:

- For humans exposed via the groundwater-to-drinking-water pathway, arsenic in CCW landfills poses a 90th percentile cancer risk of $5x10^{-4}$ for unlined units and $2x10^{-4}$ for clay-lined units. The 50th percentile risks are $1x10^{-5}$ (unlined units) and $3x10^{-6}$(clay-lined

[12] These results suggest that with the higher prevalence of composite liners in new CCW disposal facilities, future national risks from onsite CCW disposal are likely to be lower than those presented in this risk assessment (which is based on 1995 CCW WMUs).

units). Risks are higher for surface impoundments, with an arsenic cancer risk of $9x10^{-3}$ for unlined units and $3x10^{-3}$ for clay-lined units at the 90th percentile. At the 50th percentile, risks for unlined surface impoundments are $3x10^{-4}$, and clay-lined units show a risk of $9x10^{-5}$. Five additional constituents have 90th percentile noncancer risks above the criteria (HQs ranging from greater than 1 to 4) for unlined surface impoundments, including boron and cadmium, which have been cited in CCW damage cases referenced above. Boron and molybdenum show HQs of 2 and 3 for clay-lined surface impoundments. None of these noncarcinogens show HQs above 1 at the 50th percentile for any unit type.

- Arrival times of the peak concentrations at a receptor well are much longer for landfills (hundreds to thousands of years) than for surface impoundments (most less than 100 years).
- For humans exposed via the groundwater-to-surface-water (fish consumption) pathway, selenium (HQ = 2) and arsenic (cancer risk = $2x10^{-5}$) pose risks slightly above the risk criteria for unlined surface impoundments at the 90th percentile. For both constituents, lined 90th percentile risks and all 50th percentile risks are below the risk criteria. No constituents pose risks above the risk criteria for landfills at the 90th or 50th percentile.
- Waste type has little effect on landfill risk results, but in surface impoundments, risks are up to 1 order of magnitude higher for codisposed CCW and coal refuse than for conventional CCW.
- The higher risks for surface impoundments than landfills are likely due to higher waste leachate concentrations, a lower proportion of lined units, and the higher hydraulic head from the impounded liquid waste. This is consistent with damage cases reporting wet handling as a factor that can increase risks from CCW management.
- For ecological receptors exposed via surface water, risks for landfills exceed the risk criteria for boron and lead at the 90th percentile, but 50th percentile risks are well below the risk criteria. For surface impoundments, 90th percentile risks for several constituents exceed the risk criteria, with boron showing the highest risks (HQ = 2,000). Only boron exceeds the risk criteria at the 50th percentile (HQ = 4). Exceedances for boron and selenium are consistent with reported ecological damage cases, which include impacts to waterbodies through the groundwater-to-surface-water pathway.
- For ecological receptors exposed via sediment, 90th percentile risks for lead, arsenic, and cadmium exceeded the risk criteria for both landfills and surface impoundments because these constituents strongly sorb to sediments in the waterbody. The 50th percentile risks are generally an order of magnitude or more below the risk criteria.

Sensitivity analysis results indicate that for most of the scenarios evaluated (over 75 percent), the risk assessment model was most sensitive to parameters related to groundwater flow and transport: WMU infiltration rate, leachate concentration, and aquifer hydraulic conductivity and gradient. For strongly sorbing contaminants (such as lead and cadmium), variables related to sorption and travel time (adsorption coefficient, depth to groundwater, receptor well distance) are most important.

There are uncertainties associated with the CCW risk assessment, but scenario uncertainty (i.e., uncertainty about the environmental setting around the plant) has been minimized by basing the risk assessment on conditions around existing U.S. coal-fired power plants around the United States. Uncertainty in environmental setting parameters has been incorporated into the risk assessment by varying these inputs within reasonable ranges when the exact value is not known. Uncertainty in human exposure factors (such as exposure duration, body weight, and intake rates) has also been addressed through the use of national distributions.

Some uncertainties not addressed explicitly in the risk assessment have been addressed through comparisons with other studies and data sources.

- **Appropriateness of CCW leachate data.** Data on another highly sensitive parameter, leachate (porewater) constituent concentration, were available and used for CCW surface impoundments. However, available data for landfills were mainly TCLP analyses, which may not be representative of actual CCW leachate. Comparisons with recent (2006) studies of coal ash leaching processes show very good agreement for arsenic. However, although the selenium CCW data are within the range of the 2006 data, some of the higher concentrations in the 2006 data are not represented by the TCLP data. This suggests that selenium risks may be underestimated, which is consistent with selenium as a common driver of the damage cases.
- **Impacts of mercury rules (CAIR and CAMR).** While CAIR and CAMR will reduce emissions of mercury and other metals from coal-fired power plants, mercury and other more volatile metals will be transferred from the flue gas to fly ash and other air pollution control residues, including the sludge from wet scrubbers. EPA ORD has research underway to evaluate changes to CCW characteristics and leaching of mercury and other metals from CAIR and CAMR. Data from the first report (U.S. EPA, 2006) suggest that although total mercury will increase in CCW from the use of sorbents as mercury controls, the leachability of mercury may be reduced, but this work is ongoing and should be regarded as preliminary and limited at this time. For example, wet scrubbers have yet to be addressed, and initial data from both EPA and industry studies suggest that mercury may not be as stable as found from fly ash in the first report. As these data become available, EPA will consider how best to use them to update the existing risk assessment.
- **Mercury and nondetect analyses.** Because of a high proportion of nondetect values and a limited number of measurements, the risks from mercury in CCW could not be evaluated for either landfills or surface impoundments and for antimony and thallium in surface impoundments. The 2006 leaching study data suggest that mercury levels are fairly low in fly ash from coal combustion, but additional data and analyses would be required to estimate the risks from these levels.
- **Arsenic speciation.** The current model does not speciate metals in the subsurface, which is of particular concern for arsenic. Damage cases and other studies suggest that arsenic readily converts from arsenic III in CCW leachate to the less mobile arsenic V in soil and groundwater. However, model runs conducted for both species suggest that the difference in risk between the two species is only about a factor of 2, which is not enough to reduce the 90th percentile cancer risks to below the risk criteria.

Uncertainties that are more difficult to evaluate with respect to CCW risk results include the following:

- **Well distance.** Nearest well distances were taken from a survey of MSW landfills, as data were not available from CCW sites. EPA believes that this is a protective assumption because MSW landfills generally tend to be in more populated areas, but there are little data available to test this hypothesis.
- **Liner conditions.** Liner design and performance for CCW WMUs were based on data and assumptions EPA developed to be appropriate for nonhazardous industrial waste landfills. EPA believes that CCW landfills should have similar performance characteristics, but does not have the quantitative data to verify that.
- **Data gaps for ecological receptors.** Insufficient data were available to develop screening levels and quantitative risk estimates for terrestrial amphibians, but EPA acknowledges that damage cases indicate risk to terrestrial amphibian and plant communities through exposure to selenium and boron.
- **Ecosystems and receptors at risk.** Certain critical assessment endpoints were not evaluated in this analysis, including impacts on managed lands, critical habitats, and threatened and endangered species. These would be addressed through more site-specific studies on the proximity of these areas and species to CCW disposal units.
- **Synergistic risk.** The impact of exposures of multiple contaminants to human and ecological risks was not evaluated in this analysis. EPA recognizes that a single-constituent analysis may underestimate risks associated with multiple chemical exposures.

These are potentially the more significant uncertainties associated with the CCW risk assessment. Other uncertainties are discussed in Section 4.4.

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Appendix A. Constituent Data

The coal combustion waste (CCW) risk assessment addresses metals and inorganic constituents identified by EPA as potential constituents of concern in CCW (Table A-1). U.S. Environmental Protection Agency (EPA) derived waste concentrations for these constituents from its CCW constituent database, which includes analyte concentration data in three tables representing different types of waste samples: landfill leachate analyses (in mg/L), surface impoundment and landfill porewater analyses (in mg/L), and analyses of whole waste samples (in mg/kg). Each database table specifies, for most samples, the type of waste sampled and the type of coal burned at the facility.

Table A-1. Constituents Addressed in the Screening Analysis

Constituent	CAS ID	Constituent	CAS ID
Metals		***Inorganic Anions***	
Aluminum	7429-90-5	Chloride	16887-00-6
Antimony	7440-36-0	Cyanide	57-12-5
Arsenic	7440-38-2	Fluoride	16984-48-8
Barium	7440-39-3	Total Nitrate Nitrogen	14797-55-8
Beryllium	7440-41-7	Phosphate	14265-44-2
Boron	7440-42-8	Silicon	7631-86-9
Cadmium	7440-43-9	Sulfate	14808-79-8
Chromium	7440-47-3	Sulfide	18496-25-8
Cobalt	7440-48-4	***Inorganic Cations***	
Copper	7440-50-8	Ammonia	7664-41-7
Iron	7439-89-6	Calcium	7440-70-2
Lead	7439-92-1	pH	12408-02-5
Magnesium	7439-95-4	Potassium	7440-09-7
Manganese	7439-96-5	Sodium	7440-23-5
Mercury	7439-97-6	***Nonmetallic Elements***	
Molybdenum	7439-98-7	Inorganic Carbon	7440-44-0
Nickel	7440-02-0	Total Elemental Sulfur	7704-34-9
Selenium	7782-49-2	***Measurements***	
Silver	7440-22-4	Total Dissolved Solids	none
Strontium	7440-24-6	Total Organic Carbon	none
Thallium	7440-28-0	Dissolved Organic Carbon	none
Vanadium	7440-62-2		
Zinc	7440-66-6		

A.1 Data Sources

EPA prepared the CCW constituent database in 2002 and 2003. The 2003 CCW constituent database includes all of the waste characterization data used by EPA in its risk assessments in support of the March 1999 *Report to Congress: Wastes from the Combustion of Fossil Fuels* (the RTC) (U.S. EPA, 1999). In addition to the data set from the March 1999 RTC, EPA supplemented the database with the following data:

- Data submitted with public comments to EPA on the 1999 RTC
- Data submitted with public comments to EPA concerning the May 22, 2000, Final Regulatory Determination
- Data collected by and provided to EPA since the end of the public comment period on the Final Regulatory Determination
- Data identified from literature searches.

The primary sources of these additional data include the electric power industry, state and federal regulatory agencies, and scientific literature. Attachment A-1 is a complete list of the sources of data contained in the 2003 CCW constituent database.

The additional data represent a significant expansion in the quantity of characterization data available to EPA for analysis. For example, the data set used for the risk assessments supporting the RTC covered approximately 50 CCW generation and/or disposal sites. With the addition of the supplemental data, the 2003 CCW constituent database now covers more than 160 sites. The 1999 data set included approximately 10,000 individual samples of CCW. The 2003 CCW constituent database now includes more than 35,000 individual samples.

The additional data also represent an expansion in the scope of characterization data available to EPA for analysis. The 1999 data were obtained exclusively from the electric power industry. As shown in Attachment A-1, the 2003 data set includes data from other sources, such as scientific literature and state and federal regulatory agencies. The 1999 data set included analyses of whole waste samples, surface impoundment and landfill porewater analyses, and analyses of extracts obtained using the Toxicity Characteristic Leaching Procedure (TCLP), the Synthetic Precipitation Leaching Procedure (SPLP), and Extraction Procedure (EP) Toxicity leaching methods. The 2003 data set adds analyses of actual landfill leachate (e.g., obtained from leachate collection systems), analyses of extracts obtained using other leaching methods (including higher retention time leaching methods), and porewater analyses.

The 2003 CCW constituent database represents CCW characteristics across a broad cross section of the generating universe. Not only does the database include data from a large number of sites, but these sites are distributed throughout the United States, as shown in Table A-2. The database includes data for all major types of CCW (i.e., fly ash, bottom ash, flue gas desulfurization [FGD] sludge, fluidized bed combustion [FBC] fly ash, and FBC bed ash), from mixtures of CCW types that are commonly created during disposal operations (e.g., combined fly ash and bottom ash), and from CCW mixed with coal refuse (a common disposal practice). Section A.2 discusses waste types in more detail.

Table A-2. States Included in the CCW Constituent Database

Alaska	Illinois	Maryland
Arkansas	Indiana	Michigan
California	Kentucky	Ohio
Colorado	Missouri	Oklahoma
Connecticut	North Carolina	Pennsylvania
Florida	North Dakota	Tennessee
Georgia	Nebraska	Texas
Hawaii	New Mexico	Wisconsin
Iowa	Louisiana	West Virginia

The database also includes data for CCW generated from combustion of all major coal ranks: bituminous, sub-bituminous, lignite, and anthracite. Although the database does include coal type designations for most of the entries, in many cases the type is not specified. In addition, many coal plants mix coal from different sources (e.g., eastern and western coals), depending on prices and the need to reduce sulfur levels. As a result, correlations of risk results with coal types may be difficult and may not produce significant results.

A.2 Data Preparation

Table A-3 lists the waste types evaluated in the CCW risk assessment, along with the number of sites representing each waste type in the CCW constituent database. Key steps in preparing these data for screening include (1) selection and grouping of waste types to be addressed, (2) selection of the analyte data to be used, and (3) processing of these data to develop the analyte concentrations for the screening analysis.

Table A-3. Waste Streams in CCW Constituent Database

Waste Type **Waste Streams**	**Number of Sites by Waste Type[a]**		
	Landfill Leachate	**Surface Impoundment Porewater**	**Total Waste**
Conventional Combustion Waste	*97*	*13*	*62*
Ash (not otherwise specified)	43	0	30
Fly ash	61	2	33
Bottom ash & slag	24	3	23
Combined fly & bottom ash	7	4	4
FGD sludge	4	6	5
Codisposed Ash & Coal Refuse	9	5	1
Fluidized Bed Combustion Waste	*58*	*0*	*54*
Ash (not otherwise specified)	18	0	10
Fly ash	33	0	32
Bottom and bed ash	26	0	25
Combined fly & bottom ash	20	0	22

[a] Site counts by waste type from leachate, porewater, and whole waste data tables in the 2003 CCW constituent database.

A.2.1 Selection and Grouping of Waste Types of Concern

The CCW constituent database contains a variety of waste types. Some selection and grouping of these types was appropriate so that the risk assessment could evaluate risks consistently for groups of wastes that are expected to behave similarly when disposed in landfills and surface impoundments.

Combustion ash types in the CCW constituent database include fly ash, bottom ash, bed ash, slag, combined fly and bottom ash, and coal ash not otherwise specified. Based on a statistical analysis that showed no significant difference in leachate and porewater chemistry, the analysis combines data for these ash types for landfills and surface impoundments. FGD sludge is also combined with these conventional combustion ash types based on insignificant differences in porewater chemistry and the fact that FGD sludge is usually codisposed with varying amounts of fly ash and bottom ash.

CCW porewater constituent data did show that FBC wastes and codisposed ash and coal refuse (coal waste from coal crushers and other coal preparation and handling operations[1]) differ significantly from coal combustion ash in their composition and leachate chemistry, so these wastes were addressed separately in the risk analysis. FBC waste chemistry is impacted by the limestone injected with coal in FBC units for sulfur capture and tends to be very alkaline with high levels of calcium and sulfate. Coal refuse is high in pyrite, which generates sulfuric acid when disposed. As a result, combustion wastes exhibit a lower pH when codisposed with coal refuse.

A.2.2 Selection of Appropriate Analyte Data

CCW analyte concentration data represent leachate from landfills and surface impoundments and whole waste in landfills, as follows:

- Whole waste analyte concentrations (in mg/kg) represent landfill waste.
- Analyte concentrations (in mg/L) in porewater sampled from surface impoundment sediments represent surface impoundment leachate.
- Analyte concentrations for extracts from leaching methods, analyses of actual landfill leachate, and landfill porewater analyses represent landfill leachate. Because the CCW constituent database includes analyte concentrations from several leaching methods, a decision hierarchy was used to select leachate analyses to use in the risk assessment (Table A-4).

As shown in Table A-4, the methods thought to best represent long-term waste monofill porewater composition (i.e., methods with long equilibration times and low liquid-to-solid ratios) represent only a few sites, with most sites having TCLP and/or SPLP measurements. To best represent CCW landfill waste concentration at a wide variety of sites, the hierarchy rank shown in Table A-4 was used to select the best method for a particular site. For sites where two or more

[1] Coal refuse is the waste coal produced from coal handling, crushing, and sizing operations. In the CCW constituent database, codisposed coal refuse includes “combined ash and coal gob”, “combined ash and coal refuse”, and “combined bottom ash and pyrites”.

methods are available in the same rank (which often occurs for SPLP and TCLP analyses), the screening analysis uses the method with the highest analyte concentrations. This ensures that the data used in the risk assessment are the best that are available and represent a broad variety of waste disposal conditions.

Table A-4. Comparison/Hierarchy of Leaching Methods for Landfills Represented in CCW Constituent Database

Method (Rank)	Description	Advantages	Disadvantages
Landfill leachate (1)	Direct samples of landfill leachate	Most representative of leachate chemistry	Low number of sites represented
Landfill porewater (1)	Direct porewater samples from landfill	Most representative of leachate chemistry	Low number of sites represented
High retention time and low liquid-to-solid ratio (L:S) methods (2)	Waste extractions with long equilibration times (days to weeks) and low L:S	Better representation of landfill equilibration times and L:S	Low number of sites represented
Low L:S methods (3)	Waste extractions with low L:S	Better representation of landfill L:S	Low number of sites represented; equilibrium times relatively short
High retention time methods (3)	Waste extractions with long equilibration times (days to weeks)	Better representation of landfill equilibration times	Low number of sites represented; L:S relatively high
TCLP (4)	Toxicity Characteristic Leaching Procedure waste extractions	Most representative in terms of number of sites, waste types covered	High L:S (20:1) can dilute leachate concentrations; short equilibration time (18 hours) may not allow equilibrium to develop; Na-acetate buffer can overestimate leaching for some constituents (e.g., Pb)
SPLP (4)	Synthetic Precipitation Leaching Procedure and other dilute water waste extractions	More representative in terms of number of sites, waste types covered; extract similar to precipitation	High L:S (20:1) can dilute leachate concentrations; short equilibration time (18 hours) may not allow equilibrium to develop

A.2.3 Development of Waste Constituent Concentrations

To allow risk assessment results to be organized by waste constituent and waste type, CCW data were processed to produce a single concentration per waste stream (surface impoundment porewater, landfill leachate, and landfill whole waste), analyte, and site for use in the risk assessment. Data processing to prepare these analyte concentrations for the CCW risk assessment involved two steps:

1. **Calculation of average constituent concentrations by site for landfill leachate, surface impoundment porewater, and total ash concentrations.** Site averaging avoids potential bias toward sites with many analyses per analyte. During site averaging, any separate waste disposal scenarios occurring at a site (e.g., non-FBC and FBC ash) were treated as separate “sites” and were averaged independently. This approach is consistent with that used in the 1998 CCW risk analysis. As in 1998, nondetects were averaged at one-half the reported detection limit.

2. **Selection of waste concentrations from site-averaged values.** For the Monte Carlo analysis, the analysis randomly selected, by waste type/waste management unit (WMU) scenario, site-averaged leachate concentrations. For landfills, a corresponding total waste analysis was pulled from the database or calculated from a constituent-specific relationship between landfill leachate and total waste analyses.

A.3 Constituent Screening and Selection

The CCW risk assessment employed two steps to narrow the list of CCW constituents for the full-scale Monte Carlo risk assessment. Two steps were conducted to focus the full-scale analysis on the CCW constituents of most concern:

1. **Hazard Identification**, which involved collection of existing human health and ecological benchmarks for the constituents of concern. Only chemicals with benchmarks moved on to risk screening.
2. **Constituent Screening**, which compared health-based concentration benchmarks against very conservative estimates of exposure concentrations (e.g., whole waste concentrations, leaching concentrations) to quickly and simply "screen out" constituents and exposure pathways of no significant concern.

During the hazard identification step of the CCW risk assessment, constituents of potential concern were first identified by searching, from EPA and other reputable sources, for human health and ecological benchmarks for each chemical in the CCW constituent database. Table A-5 shows the result of that search; of the 41 chemicals in the database, 26 chemicals were found to have benchmarks.

Table A-5. Toxicity Assessment of CCW Constituents

Constituent	CAS ID	HHB	EcoB	Constituent	CAS ID	HHB	EcoB
Metals				***Inorganic Anions***			
Aluminum	7429-90-5	✔	✔	Chloride	16887-00-6		
Antimony	7440-36-0	✔	✔	Cyanide	57-12-5	✔	
Arsenic	7440-38-2	✔[a]	✔	Fluoride	16984-48-8	✔	
Barium	7440-39-3	✔	✔	Nitrate	14797-55-8	✔	
Beryllium	7440-41-7	✔[a]	✔	Nitrite	14797-65-0	✔	
Boron	7440-42-8	✔	✔	Phosphate	14265-44-2		
Cadmium	7440-43-9	✔[a]	✔	Silicon	7631-86-9		
Chromium	7440-47-3	✔[a]	✔	Sulfate	14808-79-8		
Cobalt	7440-48-4	✔[a]	✔	Sulfide	18496-25-8		
Copper	7440-50-8	✔[b]	✔	***Inorganic Cations***			
Iron	7439-89-6			Ammonia	7664-41-7	✔	
Lead	7439-92-1	✔[b]	✔	Calcium	7440-70-2		
Magnesium	7439-95-4			pH	12408-02-5		
Manganese	7439-96-5	✔		Potassium	7440-09-7		
Mercury	7439-97-6	✔	✔	Sodium	7440-23-5		
Molybdenum	7439-98-7	✔	✔	***Nonmetallic Elements***			
Nickel	7440-02-0	✔	✔	Carbon	7440-44-0		
Selenium	7782-49-2	✔	✔	Sulfur	7704-34-9		
Silver	7440-22-4	✔	✔	***Measurements***			
Strontium	7440-24-6	✔		Total Dissolved Solids	none		

Constituent	CAS ID	HHB	EcoB	Constituent	CAS ID	HHB	EcoB
Thallium	7440-28-0	✔	✔	Total Organic Carbon	none		
Vanadium	7440-62-2	✔	✔	Dissolved Organic Carbon	none		
Zinc	7440-66-6	✔	✔				

HHB = human health effect benchmark; EcoB = ecological benchmark.
[a] Carcinogen.
[b] Safe Drinking Water Act Action Level only.

To further narrow the list of constituents, a screening analysis (RTI, 2002) was conducted that compared health-based concentration benchmarks against very conservative estimates of exposure concentrations (e.g., 95th percentile whole waste and leachate concentrations) to quickly and simply "screen out" constituents and exposure pathways posing no significant risk to human health or the environment. Based on the number of pathways with screening failures and how much each chemical exceeded a benchmark, the constituents failing this screen were divided into two groups: (1) those of marginal concern and (2) those of greater concern. Table A-6 shows each of these groups. Constituents of greater concern were subjected to the full-scale probabilistic risk assessment described in this document.

Table A-6. Screening Analysis Results: Selection and Prioritization of CCW Chemicals for Further Analysis

Analyte	Human Health – Drinking Water		Human Health – Surface Water[a]		Ecological Risk – Surface Water		Modeling Priority
	LF Rank [maxHQ]	SI Rank [maxHQ]	LF Rank [maxHQ]	SI Rank [maxHQ]	LF Rank [maxHQ]	SI Rank [maxHQ]	
Constituents of Greater Concern (Full-Scale Analysis)							
Arsenic[b]	1 [140]	1 [1,800]	2 [22]	5 [1.7]	7 [4.9]	3 [64]	1
Boron	6 [4.0]	3 [28]	-	-	2 [660]	1 [4,700]	1
Cadmium	7 [3.4]	7 [8.9]	5 [1.4]	4 [3.7]	11 [2.0]	9 [5.2]	1
Lead	4 [16]	5 [12]	-	-	3 [79]	4 [59]	1
Mercury	-	-	1 [700]	1 [65]	1 [1,400]	2 [132]	1
Selenium	11 [1.2]	13 [2.4]	4 [4.7]	3 [9.5]	8 [3.5]	8 [7.1]	1
Thallium	3 [21]	4 [19]	3 [6.3]	2 [5.7]	-	-	1
Aluminum	-	-	-	-	5 [12]	6 [27]	2
Antimony	2 [22]	10 [5.5]	-	-	-	-	2
Barium	-	-	-	-	4 [40]	7 [7.5]	2
Cobalt		6 [11]	-	-	-	5 [27]	2
Molybdenum	5 [4.2]	8 [6.8]	-	-	-	-	2
Nitrate/Nitrite	- / 12 [1.2]	2 [60]/ 15 [1.2]	-	-	-	-	2
Constituents of Marginal Concern							
Chromium VI	8 [2.3]	12 [4.2]	-	-	12 [1.8]	10 [3.3]	3
Fluoride	10 [1.8]	11 [5.2]	-	-	-	-	3
Manganese	13 [1]	9 [5.6]	-	-	-	-	3
Vanadium	9 [2.2]	14 [2.3]	-	-	10 [2.3]	12 [2.4]	3
Beryllium	-	-	-	-	9 [2.4]	-	4

Analyte	Human Health – Drinking Water		Human Health – Surface Water[a]		Ecological Risk – Surface Water		Modeling Priority
	LF Rank [maxHQ]	SI Rank [maxHQ]	LF Rank [maxHQ]	SI Rank [maxHQ]	LF Rank [maxHQ]	SI Rank [maxHQ]	
Constituents of Greater Concern (Full-Scale Analysis)							
Copper	-	-	-	-	14 [1.6]	11 [3.1]	4
Nickel	-	16 [1.3]	-	-	-	13 [1.4]	4
Silver	-	-	-	-	6 [11]	14 [1.4]	4
Zinc	-	-	-	-	13 [1.6]	-	4

LF = landfill; maxHQ = maximum hazard quotient; SI = surface impoundment.
[a] Fish consumption pathway.
[b] Arsenic values for human health are [excess cancer risk / target risk (1E-05)].

A.4 Results

Attachment A-2 provides the site-averaged constituent data used in the full-scale CCW risk assessment by waste type/WMU scenario.

A.5 References

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Attachment A-1: Sources of Data

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Attachment A-2: CCW Constituent Data

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
11 - FBC	LF	Arsenic	0.002916667	3	3	51
11 - FBC	LF	Barium	0.339166667	3	3	174.5
11 - FBC	LF	Cadmium	0.0005	4	4	6.91875
11 - FBC	LF	Lead	0.0025	4	4	39.5
11 - FBC	LF	Mercury	0.00125	4	4	0.1325
11 - FBC	LF	Selenium	0.00225	4	2	45.5
12 - FBC	LF	Aluminum	3.4	1	0	35874.6
12 - FBC	LF	Antimony	0.27	1	0	18
12 - FBC	LF	Arsenic	0.02205	2	0	57.64333333
12 - FBC	LF	Barium	0.196	2	1	203.805
12 - FBC	LF	Boron	0.05	1	1	20.324
12 - FBC	LF	Cadmium	0.005625	2	1	0.279375
12 - FBC	LF	Lead	0.025	1	1	45.66666667
12 - FBC	LF	Mercury	0.00005	2	2	1.2575
12 - FBC	LF	Molybdenum	0.21	1	0	15.5
12 - FBC	LF	Selenium	0.04355	2	0	7.365833333
17 - FBC	LF	Aluminum	4.788	5	0	46194.8
17 - FBC	LF	Antimony	0.0708	5	2	14.60333333
17 - FBC	LF	Arsenic	0.1378	5	0	71.46666667
17 - FBC	LF	Barium	0.3512	5	1	134.975
17 - FBC	LF	Boron	0.4404	5	1	34.06333333
17 - FBC	LF	Cadmium	0.0434	5	2	3.058333333
17 - FBC	LF	Lead	0.2372	5	2	49.65
17 - FBC	LF	Mercury	0.01022	5	5	1.60345
17 - FBC	LF	Molybdenum	0.097	5	1	3.515
17 - FBC	LF	Selenium	0.06315	5	2	3.301666667
18 - FBC	LF	Aluminum	1.333333333	3	0	23501.33333
18 - FBC	LF	Antimony	0.025	3	3	5
18 - FBC	LF	Arsenic	0.025	3	3	53.33333333
18 - FBC	LF	Barium	0.175	3	1	211.3333333
18 - FBC	LF	Boron	1.341666667	3	1	532.3333333
18 - FBC	LF	Cadmium	0.025	3	3	2.5
18 - FBC	LF	Cobalt	0.025	3	3	11
18 - FBC	LF	Lead	0.025	3	3	22
18 - FBC	LF	Mercury	0.0005	3	2	0.268333333
18 - FBC	LF	Molybdenum	0.175	3	1	7.666666667
18 – FBC	LF	Selenium	0.108333333	3	1	0.5

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
18 - FBC	LF	Thallium	0.025	3	3	1
19 - FBC	LF	Arsenic	0.0875	2	1	6.25
19 - FBC	LF	Barium	0.27	2	1	39.2
19 - FBC	LF	Cadmium	0.01375	2	2	2.5
19 - FBC	LF	Lead	0.0675	2	2	3.75
19 - FBC	LF	Mercury	0.00125	2	1	0.125
19 - FBC	LF	Selenium	0.06875	2	2	6.25
20 - FBC	LF	Aluminum	10.81	12	0	34329.16522
20 - FBC	LF	Antimony	0.787	10	0	46.28125
20 - FBC	LF	Arsenic	0.035	12	0	15.03130435
20 - FBC	LF	Barium	0.381818182	11	0	255.4608696
20 - FBC	LF	Boron	0.457142857	7	0	28.0025
20 - FBC	LF	Cadmium	0.03625	8	0	2.089166667
20 - FBC	LF	Lead	0.301111111	9	0	36.20052632
20 - FBC	LF	Mercury	0.29	1	0	0.454
20 - FBC	LF	Molybdenum	0.392857143	7	0	12.10111111
20 - FBC	LF	Selenium	0.088571429	7	0	4.177333333
21 - FBC	LF	Aluminum	1.91	3	0	14677.33167
21 - FBC	LF	Antimony	0.001833333	3	3	1.083333333
21 - FBC	LF	Arsenic	0.012	3	0	10.76666667
21 - FBC	LF	Barium	0.022333333	3	2	176.2666667
21 - FBC	LF	Boron	0.036666667	3	2	14.38333333
21 - FBC	LF	Cadmium	0.002083333	3	3	0.145833333
21 - FBC	LF	Cobalt	0.008333333	3	2	5.756666667
21 - FBC	LF	Lead	0.009166667	3	3	27.3
21 - FBC	LF	Mercury	0.000133333	3	2	0.431666667
21 - FBC	LF	Molybdenum	0.0125	3	3	3.708333333
21 - FBC	LF	Selenium	0.016666667	3	0	10.9
2-18 - Ash	LF	Arsenic	0.41794375	16	3	
2-18 - Ash	LF	Barium	0.4305625	16	0	
2-18 - Ash	LF	Boron	1.0160625	16	0	
2-18 - Ash	LF	Cadmium	0.05825	16	11	
2-18 - Ash	LF	Lead	0.2819375	16	11	
2-18 - Ash	LF	Mercury	0.000115625	16	16	
2-18 - Ash	LF	Selenium	0.01534375	16	8	
22 - FBC	LF	Arsenic	0.055	5	3	
22 - FBC	LF	Barium	0.5405	5	1	
22 - FBC	LF	Cadmium	0.003	5	5	
22 - FBC	LF	Lead	0.015	5	5	
22 - FBC	LF	Mercury	0.0002	5	3	
22 - FBC	LF	Molybdenum	0.0125	2	2	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
22 - FBC	LF	Selenium	0.032	5	5	
23 - FBC	LF	Barium	0.81	4	0	
25 - FBC	LF	Arsenic	0.125	1	1	
25 - FBC	LF	Barium	2.5	1	1	
25 - FBC	LF	Cadmium	0.025	1	1	
25 - FBC	LF	Lead	0.125	1	1	
25 - FBC	LF	Mercury	0.005	1	1	
25 - FBC	LF	Selenium	0.025	1	1	
28 - FBC	LF	Barium	2.525	2	0	235.11875
30 - FBC	LF	Aluminum	6.894555556	18	7	28246.46923
30 - FBC	LF	Antimony	0.548082353	17	2	61.49315385
30 - FBC	LF	Arsenic	0.050694444	18	3	48.55980769
30 - FBC	LF	Barium	0.286388889	18	6	120.0687692
30 - FBC	LF	Boron	0.31759375	16	7	30.83913462
30 - FBC	LF	Cadmium	0.023125	14	3	1.916230769
30 - FBC	LF	Lead	0.240805556	18	4	39.36092308
30 - FBC	LF	Mercury	0.000744444	18	17	10.91689923
30 - FBC	LF	Molybdenum	0.138125	16	10	14.50257692
30 - FBC	LF	Selenium	0.10475	16	10	5.603596154
31 - FBC	LF	Aluminum	0.28	1	0	29437.5
31 - FBC	LF	Antimony	0.00065	1	1	5.0325
31 - FBC	LF	Arsenic	0.0687	4	2	26.825
31 - FBC	LF	Barium	0.58275	4	0	170.25
31 - FBC	LF	Boron	26.7	1	0	930
31 - FBC	LF	Cadmium	0.02775	4	3	5.45
31 - FBC	LF	Cobalt	0.0065	1	0	6.42
31 - FBC	LF	Lead	0.03025	4	3	1.19
31 - FBC	LF	Mercury	0.00095	4	1	0.61
31 - FBC	LF	Molybdenum	0.085	1	0	8
31 - FBC	LF	Selenium	0.06485	4	2	7.54
32 - FBC	LF	Arsenic	0.35	1	1	1.4
32 - FBC	LF	Barium	0.085	1	0	
32 - FBC	LF	Cadmium	0.005	1	1	0.009
32 - FBC	LF	Lead	0.05	1	1	0.45
32 - FBC	LF	Mercury	0.0001	1	1	0.03
32 - FBC	LF	Selenium	0.175	1	1	3.5
33 - FBC	LF	Arsenic	0.015	1	1	
33 - FBC	LF	Barium	42	1	0	
33 - FBC	LF	Boron	0.06	1	0	
33 - FBC	LF	Cadmium	0.00125	1	1	
33 - FBC	LF	Cobalt	0.0025	1	1	
33 - FBC	LF	Mercury	0.00005	1	1	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
33 - FBC	LF	Selenium	0.01	1	1	
35 - FBC	LF	Arsenic	0.015	1	1	
35 - FBC	LF	Barium	2.6	1	0	
35 - FBC	LF	Cadmium	0.009	1	0	
35 - FBC	LF	Lead	0.035	1	1	
35 - FBC	LF	Mercury	0.00025	1	1	
35 - FBC	LF	Selenium	0.2	1	0	
37 - FBC	LF	Arsenic	0.011102941	17	9	5.79
37 - FBC	LF	Barium	2.104705882	17	2	
37 - FBC	LF	Boron	1.125	5	1	15.9
37 - FBC	LF	Cadmium	0.046176471	17	4	4.183333333
37 - FBC	LF	Cobalt	0.246	5	0	
37 - FBC	LF	Lead	0.287352941	17	6	55
37 - FBC	LF	Mercury	0.001314706	17	4	0.01125
37 - FBC	LF	Selenium	0.01075	17	9	3.42
38 - FBC	LF	Aluminum	2.256666667	9	2	26711.25
38 - FBC	LF	Antimony	0.213069444	9	6	11.27770833
38 - FBC	LF	Arsenic	0.024554444	9	3	25.136075
38 - FBC	LF	Barium	0.178888889	9	4	181.0083333
38 - FBC	LF	Boron	0.346555556	9	2	26.98916667
38 - FBC	LF	Cadmium	0.007388889	9	5	0.71625
38 - FBC	LF	Cobalt	0.008566667	3	2	4.515
38 - FBC	LF	Lead	0.0565	9	6	28.54166667
38 - FBC	LF	Mercury	0.000344444	9	8	0.18195
38 - FBC	LF	Molybdenum	0.177375	8	2	14.1875
38 - FBC	LF	Selenium	0.088561111	9	4	7.682450833
39 - FBC	LF	Arsenic	0.075	1	1	14.5
39 - FBC	LF	Barium	0.395	2	1	590
39 - FBC	LF	Boron	0.76	1	0	
39 - FBC	LF	Cadmium	0.005	1	1	0.5
39 - FBC	LF	Lead	0.025	1	1	15
39 - FBC	LF	Mercury	0.00025	1	1	0.17
39 - FBC	LF	Molybdenum	0.14	1	0	13.5
39 - FBC	LF	Selenium	0.025	1	1	21.5
4 - FBC	LF	Aluminum	13.556	5	0	16084.68429
4 - FBC	LF	Antimony	0.2236	5	2	26.78817857
4 - FBC	LF	Arsenic	0.271	5	0	28.03585714
4 - FBC	LF	Barium	0.6346	5	1	154.95
4 - FBC	LF	Boron	0.693	4	0	13.026
4 - FBC	LF	Cadmium	0.0115	5	2	0.646539286
4 - FBC	LF	Lead	0.1834	5	1	18.35671429
4 - FBC	LF	Mercury	0.00005	5	5	0.087192857

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
4 - FBC	LF	Molybdenum	0.286666667	3	0	16.18257143
4 - FBC	LF	Selenium	0.0620625	4	2	1.505421429
41 - FBC	LF	Antimony	0.025	5	5	1.551333333
41 - FBC	LF	Arsenic	0.035471698	53	50	13.72255319
41 - FBC	LF	Barium	0.095694444	54	25	19.05490196
41 - FBC	LF	Cadmium	0.022355769	52	51	0.427826087
41 - FBC	LF	Lead	0.017548077	52	51	0.935208333
41 - FBC	LF	Mercury	0.000596154	52	50	0.119542553
41 - FBC	LF	Selenium	0.024433962	53	51	1.505744681
41 - FBC	LF	Thallium	0.031	5	4	3.662790698
42 - FBC	LF	Arsenic	0.0125	2	2	
42 - FBC	LF	Barium	0.1625	2	1	
42 - FBC	LF	Cadmium	0.005	2	2	
42 - FBC	LF	Lead	0.0075	2	2	
42 - FBC	LF	Mercury	0.0005	2	2	
42 - FBC	LF	Selenium	0.0125	2	2	
43 - FBC	LF	Arsenic	0.0125	2	2	
43 - FBC	LF	Barium	0.0875	2	1	
43 - FBC	LF	Cadmium	0.005	2	2	
43 - FBC	LF	Lead	0.0075	2	2	
43 - FBC	LF	Mercury	0.0005	2	2	
43 - FBC	LF	Selenium	0.08625	2	1	
6 - FBC	LF	Aluminum	0.1525	2	1	42736.5
6 - FBC	LF	Antimony	0.05	2	2	16.25
6 - FBC	LF	Arsenic	0.09125	2	1	126.6
6 - FBC	LF	Barium	0.285	2	0	221.5
6 - FBC	LF	Boron	0.1425	2	1	73.8
6 - FBC	LF	Cadmium	0.0025	2	2	1.29625
6 - FBC	LF	Lead	0.01375	2	2	8.1125
6 - FBC	LF	Mercury	0.00005	2	2	1.16
6 - FBC	LF	Molybdenum	0.09	2	0	1.425
6 - FBC	LF	Selenium	0.1025	2	1	84.5625
Amerikohl - FBC	LF	Aluminum	0.753333333	3	0	51600
Amerikohl - FBC	LF	Antimony	0.345	3	3	20
Amerikohl - FBC	LF	Arsenic	0.024166667	3	3	114
Amerikohl - FBC	LF	Barium	0.1	3	3	140
Amerikohl - FBC	LF	Boron	0.346666667	3	1	60
Amerikohl - FBC	LF	Cadmium	0.004166667	3	3	0.15
Amerikohl - FBC	LF	Cobalt	0.175	3	3	30
Amerikohl - FBC	LF	Lead	0.009166667	3	3	23
Amerikohl - FBC	LF	Mercury	0.0005	3	3	0.15
Amerikohl - FBC	LF	Molybdenum	0.266666667	3	1	10

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Amerikohl - FBC	LF	Nitrate/Nitrite	3.15	3	3	
Amerikohl - FBC	LF	Selenium	0.044166667	3	3	3.5
Arkwright - Ash	LF	Arsenic	0.07	1	0	
Arkwright - Ash	LF	Barium	0.4	1	0	
Arkwright - Ash	LF	Cadmium	0.01	1	0	
Arkwright - Ash	LF	Lead	0.04	1	0	
Arkwright - Ash	LF	Selenium	0.02	1	0	
Barry - Ash	LF	Arsenic	1	1	0	
Barry - Ash	LF	Barium	0.7	1	0	
Barry - Ash	LF	Cadmium	0.005	1	0	
Barry - Ash	LF	Lead	0.04	1	0	
Barry - Ash	LF	Selenium	0.07	1	0	
Belle Ayr - Ash	LF	Aluminum	0.036666667	3	0	
Belle Ayr - Ash	LF	Antimony	0.021	2	0	
Belle Ayr - Ash	LF	Arsenic	0.181	3	0	
Belle Ayr - Ash	LF	Barium	1.163333333	3	0	
Belle Ayr - Ash	LF	Cobalt	0.0075	2	0	
Belle Ayr - Ash	LF	Molybdenum	0.325	3	0	
Belle Ayr - Ash	LF	Selenium	0.652333333	3	0	
Big Gorilla Pit - FBC	LF	Aluminum	3.774166667	12	0	18440.58824
Big Gorilla Pit - FBC	LF	Antimony	0.037166667	12	1	1.244485294
Big Gorilla Pit - FBC	LF	Arsenic	0.023181818	22	21	7.534117647
Big Gorilla Pit - FBC	LF	Barium	0.243636364	11	3	147.7320588
Big Gorilla Pit - FBC	LF	Boron	0.677916667	12	2	29.64058824
Big Gorilla Pit - FBC	LF	Cadmium	0.015227273	22	22	0.58728125
Big Gorilla Pit - FBC	LF	Cobalt	0.008553571	14	11	2.374214286
Big Gorilla Pit - FBC	LF	Lead	0.08125	12	7	19.51823529
Big Gorilla Pit - FBC	LF	Mercury	0.001704545	22	19	0.302990909
Big Gorilla Pit - FBC	LF	Molybdenum	0.1202	10	1	6.429333333
Big Gorilla Pit - FBC	LF	Nitrate/Nitrite	1.755857143	14	3	
Big Gorilla Pit - FBC	LF	Selenium	0.10975	12	1	7.159397059
Bowen - Ash	LF	Arsenic	0.6	1	0	68
Bowen - Ash	LF	Barium	0.3	1	0	974
Bowen - Ash	LF	Cadmium	0.01	1	0	0.7
Bowen - Ash	LF	Lead	0.04	1	0	63.9
Bowen - Ash	LF	Selenium	0.1	1	0	
Branch - Ash	LF	Arsenic	0.04	1	0	
Branch - Ash	LF	Barium	0.5	1	0	
Branch - Ash	LF	Cadmium	0.01	1	0	
Branch - Ash	LF	Lead	0.04	1	0	
Branch - Ash	LF	Selenium	0.06	1	0	
Buckheart Mine - Ash	LF	Antimony	0.01854	40	14	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Buckheart Mine - Ash	LF	Arsenic	0.122357143	42	13	
Buckheart Mine - Ash	LF	Barium	0.364809524	42	0	
Buckheart Mine - Ash	LF	Boron	9.998738095	42	0	
Buckheart Mine - Ash	LF	Cadmium	0.0235	42	8	
Buckheart Mine - Ash	LF	Cobalt	0.048047619	42	17	
Buckheart Mine - Ash	LF	Lead	0.27887619	42	9	
Buckheart Mine - Ash	LF	Mercury	0.000107143	42	40	
Buckheart Mine - Ash	LF	Selenium	0.118266667	42	26	
Buckheart Mine - Ash	LF	Thallium	0.017875	40	10	
Buckheart Mine - FBC	LF	Antimony	0.0018125	8	8	
Buckheart Mine - FBC	LF	Arsenic	0.0465	8	5	
Buckheart Mine - FBC	LF	Barium	0.560125	8	1	
Buckheart Mine - FBC	LF	Boron	3.157	8	0	
Buckheart Mine - FBC	LF	Cadmium	0.0033125	8	7	
Buckheart Mine - FBC	LF	Cobalt	0.02875	8	7	
Buckheart Mine - FBC	LF	Lead	0.036	8	4	
Buckheart Mine - FBC	LF	Mercury	0.0005	8	4	
Buckheart Mine - FBC	LF	Selenium	0.050625	8	5	
Buckheart Mine - FBC	LF	Thallium	0.001	8	8	
CAER - Ash	LF	Arsenic	1.132	5	0	77.32222222
CAER - Ash	LF	Barium	0.315	5	0	537.6666667
CAER - Ash	LF	Cadmium	0.0942	5	0	
CAER - Ash	LF	Lead	0.1	5	2	73.62375
CAER - Ash	LF	Mercury	0.00025	5	5	
CAER - Ash	LF	Selenium	0.103	5	0	
Canton Site - Ash	LF	Aluminum	9.818127778	36	0	
Canton Site - Ash	LF	Arsenic	0.0025	2	2	
Canton Site - Ash	LF	Barium	3.0156	10	0	
Canton Site - Ash	LF	Boron	18.62468571	35	0	
Canton Site - Ash	LF	Cadmium	0.0005	2	2	
Canton Site - Ash	LF	Cobalt	0.02	1	1	
Canton Site - Ash	LF	Lead	0.1865	2	0	
Canton Site - Ash	LF	Mercury	0.0001	1	1	
Canton Site - Ash	LF	Molybdenum	30.9359	20	0	
Canton Site - Ash	LF	Nitrate/Nitrite	0.095	1	0	
Canton Site - Ash	LF	Selenium	0.0374	1	0	
Canton Site - FBC	LF	Aluminum	2.461866667	24	0	
Canton Site - FBC	LF	Arsenic	0.005	1	1	
Canton Site - FBC	LF	Barium	0.02	1	0	
Canton Site - FBC	LF	Boron	1.5602625	16	0	
Canton Site - FBC	LF	Cadmium	0.066	1	0	
Canton Site - FBC	LF	Lead	0.062	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Canton Site – FBC	LF	Mercury	0.0005	1	1	
Canton Site – FBC	LF	Molybdenum	1.768009524	21	0	
Canton Site – FBC	LF	Selenium	0.005	1	1	
Central Cleaning Plant - Ash	LF	Antimony	0.008205882	17	17	
Central Cleaning Plant - Ash	LF	Arsenic	0.005	17	17	
Central Cleaning Plant - Ash	LF	Barium	0.168164706	17	0	
Central Cleaning Plant - Ash	LF	Boron	7.213823529	17	0	
Central Cleaning Plant - Ash	LF	Cadmium	0.004117647	17	16	
Central Cleaning Plant - Ash	LF	Cobalt	0.019588235	17	15	
Central Cleaning Plant - Ash	LF	Lead	0.022782353	17	11	
Central Cleaning Plant - Ash	LF	Mercury	0.000568824	17	11	
Central Cleaning Plant - Ash	LF	Selenium	0.040211765	17	0	
Central Cleaning Plant - Ash	LF	Thallium	0.005	17	17	
CL - Ash and Coal Refuse	LF	Aluminum	2.58	3	0	
CL - Ash and Coal Refuse	LF	Antimony	0.0041	3	0	
CL - Ash and Coal Refuse	LF	Arsenic	0.121266667	3	0	
CL - Ash and Coal Refuse	LF	Barium	3.63	3	0	
CL - Ash and Coal Refuse	LF	Boron	0.103133333	3	0	
CL - Ash and Coal Refuse	LF	Cadmium	0.001	3	0	
CL - Ash and Coal Refuse	LF	Cobalt	0.006066667	3	1	
CL - Ash and Coal Refuse	LF	Lead	0.003533333	3	0	
CL - Ash and Coal Refuse	LF	Mercury	0.00005	6	6	
CL - Ash and Coal Refuse	LF	Selenium	0.0452	3	0	
CL - Ash and Coal Refuse	LF	Thallium	0.003483333	3	1	
Coal Creek - Ash	LF	Arsenic	0.0109	2	0	0.086
Coal Creek - Ash	LF	Barium	0.6105	2	0	4.76
Coal Creek - Ash	LF	Boron	6.22	2	0	1.1105
Coal Creek - Ash	LF	Cadmium	0.00015	2	2	0.00045
Coal Creek - Ash	LF	Lead	0.001	2	2	0.02025
Coal Creek - Ash	LF	Mercury	0.000005	2	2	0.0006
Coal Creek - Ash	LF	Selenium	0.0555	2	1	0.00505
Colver Site - FBC	LF	Aluminum	0.248333333	6	1	78878.83333
Colver Site - FBC	LF	Antimony	0.196666667	6	2	166.5
Colver Site - FBC	LF	Arsenic	0.0875	6	1	124.2
Colver Site - FBC	LF	Barium	0.291666667	6	0	443.8333333
Colver Site - FBC	LF	Boron	0.261666667	6	1	62.6
Colver Site - FBC	LF	Cadmium	0.016666667	6	2	9.994166667
Colver Site - FBC	LF	Lead	0.190833333	6	2	192.075
Colver Site - FBC	LF	Mercury	0.00015	6	5	0.586666667
Colver Site - FBC	LF	Molybdenum	0.143333333	6	0	30.65833333
Colver Site - FBC	LF	Selenium	0.48	6	1	68.70833333
Conemaugh - Ash	LF	Aluminum	1.245	2	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Conemaugh - Ash	LF	Antimony	0.075	1	1	
Conemaugh - Ash	LF	Arsenic	0.388333333	3	1	
Conemaugh - Ash	LF	Barium	0.331666667	3	0	
Conemaugh - Ash	LF	Boron	0.91	1	0	
Conemaugh - Ash	LF	Cadmium	0.01	3	0	
Conemaugh - Ash	LF	Cobalt	0.026	1	0	
Conemaugh - Ash	LF	Lead	0.1	2	2	
Conemaugh - Ash	LF	Mercury	0.00055	2	2	
Conemaugh - Ash	LF	Molybdenum	0.355	2	0	
Conemaugh - Ash	LF	Selenium	0.295	2	1	
Conemaugh - Ash	LF	Thallium	0.024	1	0	
Conemaugh - Ash and Coal Refuse	LF	Aluminum	1.467666667	3	0	
Conemaugh - Ash and Coal Refuse	LF	Antimony	0.075	3	3	
Conemaugh - Ash and Coal Refuse	LF	Arsenic	0.625	2	2	
Conemaugh - Ash and Coal Refuse	LF	Barium	0.145666667	3	0	
Conemaugh - Ash and Coal Refuse	LF	Boron	0.095	2	0	
Conemaugh - Ash and Coal Refuse	LF	Cadmium	0.002	3	3	
Conemaugh - Ash and Coal Refuse	LF	Cobalt	0.009	1	0	
Conemaugh - Ash and Coal Refuse	LF	Lead	0.073333333	3	2	
Conemaugh - Ash and Coal Refuse	LF	Mercury	0.0004	3	2	
Conemaugh - Ash and Coal Refuse	LF	Molybdenum	0.01	1	0	
Conemaugh - Ash and Coal Refuse	LF	Selenium	0.179833333	3	1	
Conemaugh - Ash and Coal Refuse	LF	Thallium	0.005	1	0	
Crist - Ash	LF	Arsenic	0.02	1	0	
Crist - Ash	LF	Barium	0.1	1	0	
Crist - Ash	LF	Cadmium	0.02	1	0	
Crist - Ash	LF	Lead	0.003	1	0	
Crist - Ash	LF	Selenium	0.05	1	0	
Crown III - Ash	LF	Antimony	0.071159259	54	10	
Crown III - Ash	LF	Arsenic	0.352503226	62	29	
Crown III - Ash	LF	Barium	0.279112903	62	3	
Crown III - Ash	LF	Boron	22.93277419	62	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Crown III - Ash	LF	Cadmium	0.128258065	62	3	
Crown III - Ash	LF	Cobalt	0.101225806	62	17	
Crown III - Ash	LF	Lead	0.605616935	62	19	
Crown III - Ash	LF	Mercury	0.000104839	62	61	
Crown III - Ash	LF	Molybdenum	0.588888889	9	4	
Crown III - Ash	LF	Selenium	0.03946129	62	46	
Crown III - Ash	LF	Thallium	0.0645	54	18	
Crown III - FBC	LF	Antimony	0.0135	17	9	
Crown III - FBC	LF	Arsenic	0.034822581	31	26	3.766666667
Crown III - FBC	LF	Barium	0.346774194	31	2	150
Crown III - FBC	LF	Boron	2.815296296	27	1	
Crown III - FBC	LF	Cadmium	0.011241935	31	22	2.17
Crown III - FBC	LF	Cobalt	0.02475	24	16	
Crown III - FBC	LF	Lead	0.068645161	31	17	8.233333333
Crown III - FBC	LF	Mercury	0.000164516	31	27	0.381
Crown III - FBC	LF	Molybdenum	0.1522	10	2	
Crown III - FBC	LF	Selenium	0.061467742	31	27	3.3
Crown III - FBC	LF	Thallium	0.004941176	17	11	
CTL-V - Ash	LF	Antimony	0.26	1	0	
CTL-V - Ash	LF	Arsenic	0.037	1	0	
CTL-V - Ash	LF	Barium	0.247	1	0	
CTL-V - Ash	LF	Cadmium	0.04	1	0	
CTL-V - Ash	LF	Lead	0.072	1	0	
CTL-V - Ash	LF	Mercury	0.001	1	0	
CTL-V - Ash	LF	Selenium	0.014	1	0	
CTL-V - Ash	LF	Thallium	0.01	1	0	
CY - Ash	LF	Aluminum	4.735	2	0	
CY - Ash	LF	Antimony	0.0078	2	0	
CY - Ash	LF	Arsenic	0.04825	2	0	
CY - Ash	LF	Barium	1.2395	2	0	
CY - Ash	LF	Boron	6.13	2	0	
CY - Ash	LF	Cadmium	0.0002075	2	1	
CY - Ash	LF	Cobalt	0.001915	4	4	
CY - Ash	LF	Lead	0.003555	2	1	
CY - Ash	LF	Mercury	0.000265	2	0	
CY - Ash	LF	Selenium	0.004825	2	1	
CY - Ash	LF	Thallium	0.00196	4	4	
Dairyland Power Coop - Ash	LF	Arsenic	0.0328625	8	0	
Dairyland Power Coop - Ash	LF	Barium	0.058740741	27	0	
Dairyland Power Coop - Ash	LF	Boron	68.03979592	49	0	
Dairyland Power Coop - Ash	LF	Cadmium	0.00539	34	0	
Dairyland Power Coop - Ash	LF	Lead	0.0046	7	2	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Dairyland Power Coop - Ash	LF	Mercury	0.000223	2	1	
Dairyland Power Coop - Ash	LF	Selenium	0.0696375	8	0	
Daniel - Ash	LF	Arsenic	0.2	1	0	
Daniel - Ash	LF	Barium	0.4	1	0	
Daniel - Ash	LF	Cadmium	0.001	1	1	
Daniel - Ash	LF	Lead	0.001	1	1	
Daniel - Ash	LF	Selenium	0.001	1	1	
Deer Ridge Mine - Ash	LF	Aluminum	0.5941	10	1	64681.487
Deer Ridge Mine - Ash	LF	Arsenic	0.0029	10	6	21.29419
Deer Ridge Mine - Ash	LF	Barium	0.1448	10	2	258.468
Deer Ridge Mine - Ash	LF	Boron	1.228	10	2	179.354
Deer Ridge Mine - Ash	LF	Cadmium	0.01365	10	1	0.94425
Deer Ridge Mine - Ash	LF	Lead	0.0253	10	2	58.48
Deer Ridge Mine - Ash	LF	Mercury	0.00011025	10	10	0.1158
Deer Ridge Mine - Ash	LF	Molybdenum	0.0756	10	4	6.6287
Deer Ridge Mine - Ash	LF	Nitrate/Nitrite	0.095	3	2	
Deer Ridge Mine - Ash	LF	Selenium	0.01022	10	2	13.1061
DPC - Ash	LF	Antimony	0.04	2	1	0.475
DPC - Ash	LF	Arsenic	0.051	2	0	55.085
DPC - Ash	LF	Barium	0.28	2	0	37.7
DPC - Ash	LF	Boron	27.945	2	0	404.05
DPC - Ash	LF	Cadmium	0.005	4	4	0.56
DPC - Ash	LF	Lead	0.025	4	4	28.7
DPC - Ash	LF	Mercury	0.001	2	2	0.127
DPC - Ash	LF	Nitrate/Nitrite	2.5	2	0	0.2425
DPC - Ash	LF	Selenium	0.046	2	0	3.4445
EERC - Ash	LF	Mercury	0.000025	4	4	
Elkhart Mine - Ash	LF	Antimony	0.025192308	52	46	
Elkhart Mine - Ash	LF	Arsenic	0.043571429	77	71	
Elkhart Mine - Ash	LF	Barium	0.495324675	77	23	
Elkhart Mine - Ash	LF	Boron	6.88961039	77	0	
Elkhart Mine - Ash	LF	Cadmium	0.022551948	77	41	
Elkhart Mine - Ash	LF	Cobalt	0.012785714	77	57	
Elkhart Mine - Ash	LF	Lead	0.027987013	77	66	
Elkhart Mine - Ash	LF	Mercury	0.000148052	77	68	
Elkhart Mine - Ash	LF	Selenium	0.036649351	77	64	
Elkhart Mine - Ash	LF	Thallium	0.015942308	52	48	
Elkhart Mine - FBC	LF	Antimony	0.021875	16	15	
Elkhart Mine - FBC	LF	Arsenic	0.034512195	41	37	
Elkhart Mine - FBC	LF	Barium	0.525365854	41	5	
Elkhart Mine - FBC	LF	Boron	13.13829268	41	0	
Elkhart Mine - FBC	LF	Cadmium	0.003536585	41	41	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Elkhart Mine - FBC	LF	Cobalt	0.007219512	41	39	
Elkhart Mine - FBC	LF	Lead	0.017195122	41	34	
Elkhart Mine - FBC	LF	Mercury	0.000104878	41	40	
Elkhart Mine - FBC	LF	Selenium	0.035365854	41	33	
Elkhart Mine - FBC	LF	Thallium	0.02390625	16	15	
FBX - Ash	LF	Arsenic	0.0025	2	2	
FBX - Ash	LF	Barium	29.6225	2	1	
FBX - Ash	LF	Cadmium	0.2	2	2	
FBX - Ash	LF	Lead	0.5	2	2	
FBX - Ash	LF	Mercury	0.00025	2	2	
FBX - Ash	LF	Selenium	0.01375	2	2	
FC - Ash and Coal Refuse	LF	Aluminum	13.8	2	0	
FC - Ash and Coal Refuse	LF	Antimony	0.00105	4	4	
FC - Ash and Coal Refuse	LF	Arsenic	0.005	2	0	
FC - Ash and Coal Refuse	LF	Barium	0.602	2	0	
FC - Ash and Coal Refuse	LF	Boron	2.54	2	0	
FC - Ash and Coal Refuse	LF	Cadmium	0.00015	4	4	
FC - Ash and Coal Refuse	LF	Cobalt	0.0029	2	0	
FC - Ash and Coal Refuse	LF	Lead	0.00345	2	0	
FC - Ash and Coal Refuse	LF	Mercury	0.00005	4	4	
FC - Ash and Coal Refuse	LF	Selenium	0.01765	2	0	
FC - Ash and Coal Refuse	LF	Thallium	0.00185	4	4	
Florence Mine - Ash	LF	Aluminum	0.03	1	0	
Florence Mine - Ash	LF	Antimony	0.005	1	1	
Florence Mine - Ash	LF	Arsenic	0.07	1	0	
Florence Mine - Ash	LF	Barium	2.23	1	0	
Florence Mine - Ash	LF	Boron	0.01	1	1	
Florence Mine - Ash	LF	Cadmium	0.01	1	1	
Florence Mine - Ash	LF	Lead	0.001	1	0	
Florence Mine - Ash	LF	Mercury	0.002	1	0	
Florence Mine - Ash	LF	Molybdenum	0.01	1	1	
Florence Mine - Ash	LF	Nitrate/Nitrite	1.2	1	0	
Florence Mine - Ash	LF	Selenium	0.06	1	0	
Fran Site - FBC	LF	Aluminum	0.32	1	0	
Fran Site - FBC	LF	Antimony	0.005	1	1	
Fran Site - FBC	LF	Arsenic	0.02	1	0	
Fran Site - FBC	LF	Barium	0.08	1	0	
Fran Site - FBC	LF	Boron	0.43	1	0	
Fran Site - FBC	LF	Cadmium	0.005	1	1	
Fran Site - FBC	LF	Lead	0.005	1	1	
Fran Site - FBC	LF	Nitrate/Nitrite	1.22	1	0	
Fran Site - FBC	LF	Selenium	0.03	1	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
FW - FBC	LF	Arsenic	0.02525	4	3	
FW - FBC	LF	Barium	0.304	4	0	
FW - FBC	LF	Cadmium	0.005	4	4	
FW - FBC	LF	Lead	0.05	4	4	
FW - FBC	LF	Mercury	0.001	4	4	
FW - FBC	LF	Selenium	0.1	4	4	
Gadsden - Ash	LF	Arsenic	0.2	1	0	
Gadsden - Ash	LF	Barium	0.3	1	0	
Gadsden - Ash	LF	Cadmium	0.01	1	0	
Gadsden - Ash	LF	Lead	0.04	1	0	
Gadsden - Ash	LF	Selenium	0.03	1	0	
Gale - Ash	LF	Aluminum	3.1	1	0	13630
Gale - Ash	LF	Antimony	0.03	1	0	3
Gale - Ash	LF	Arsenic	0.42	1	0	51.5
Gale - Ash	LF	Barium	1.7	1	0	143
Gale - Ash	LF	Boron	0.22	1	0	25
Gale - Ash	LF	Cadmium	0.01	1	0	1
Gale - Ash	LF	Lead	0.23	1	0	21
Gale - Ash	LF	Molybdenum	0.05	1	0	5
Gale - Ash	LF	Selenium	0.1	1	0	4.4
Gaston - Ash	LF	Arsenic	1.8	1	0	
Gaston - Ash	LF	Barium	0.3	1	0	
Gaston - Ash	LF	Cadmium	0.01	1	0	
Gaston - Ash	LF	Lead	0.05	1	0	
Gaston - Ash	LF	Selenium	0.003	1	0	
Gorgas - Ash	LF	Arsenic	1.6	1	0	
Gorgas - Ash	LF	Barium	0.3	1	0	
Gorgas - Ash	LF	Cadmium	0.01	1	0	
Gorgas - Ash	LF	Lead	0.04	1	0	
Gorgas - Ash	LF	Selenium	0.002	1	0	
Greene Co - Ash	LF	Arsenic	1.1	1	0	
Greene Co - Ash	LF	Barium	0.4	1	0	
Greene Co - Ash	LF	Cadmium	0.01	1	0	
Greene Co - Ash	LF	Lead	0.04	1	0	
Greene Co - Ash	LF	Selenium	0.003	1	0	
HA - Ash and Coal Refuse	LF	Aluminum	1.71925	4	0	5666.666667
HA - Ash and Coal Refuse	LF	Antimony	0.003905	4	2	
HA - Ash and Coal Refuse	LF	Arsenic	0.024975	4	0	9.666666667
HA - Ash and Coal Refuse	LF	Barium	1.01675	4	0	186.6666667
HA - Ash and Coal Refuse	LF	Boron	0.64545	4	0	14
HA - Ash and Coal Refuse	LF	Cadmium	0.0039275	4	0	0.25
HA - Ash and Coal Refuse	LF	Cobalt	0.01517875	4	1	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
HA - Ash and Coal Refuse	LF	Lead	0.00378	4	2	8.7
HA - Ash and Coal Refuse	LF	Mercury	0.0001	4	0	0.065
HA - Ash and Coal Refuse	LF	Selenium	0.005025	4	0	0.534166667
HA - Ash and Coal Refuse	LF	Thallium	0.00196	8	8	
Hammond - Ash	LF	Arsenic	0.1	1	0	
Hammond - Ash	LF	Barium	0.3	1	0	
Hammond - Ash	LF	Cadmium	0.01	1	0	
Hammond - Ash	LF	Lead	0.05	1	0	
Hammond - Ash	LF	Selenium	0.02	1	0	
Harrim 3019 - Ash	LF	Aluminum	5.21	1	0	46577
Harrim 3019 - Ash	LF	Antimony	0.0058	1	0	646.4
Harrim 3019 - Ash	LF	Arsenic	0.178	1	0	50.43172727
Harrim 3019 - Ash	LF	Barium	0.32	1	0	319.89
Harrim 3019 - Ash	LF	Molybdenum	0.594	1	0	17.9
Harrim 3019 - Ash	LF	Nitrate/Nitrite	1.99	1	0	
Harrim 3019 - Ash	LF	Selenium	0.0468	1	0	1.405714286
Harrim 3019 - FBC	LF	Aluminum	0.67375	8	0	
Harrim 3019 - FBC	LF	Antimony	0.002	1	0	
Harrim 3019 - FBC	LF	Barium	0.465888889	9	0	
Harrim 3019 - FBC	LF	Boron	0.07	1	0	
Harrim 3019 - FBC	LF	Cobalt	0.1385	6	0	
Harrim 3019 - FBC	LF	Lead	0.24	5	0	
Harrim 3019 - FBC	LF	Molybdenum	0.347714286	7	0	
Harrim 3019 - FBC	LF	Nitrate/Nitrite	0.199333333	3	0	
Harrim 3019 - FBC	LF	Selenium	0.019	2	0	
Industry Mine - Ash	LF	Antimony	0.031597143	70	12	
Industry Mine - Ash	LF	Arsenic	0.050248454	97	51	
Industry Mine - Ash	LF	Barium	0.328329897	97	13	
Industry Mine - Ash	LF	Boron	4.719969072	97	0	
Industry Mine - Ash	LF	Cadmium	0.059061856	97	7	
Industry Mine - Ash	LF	Cobalt	0.120010309	97	30	
Industry Mine - Ash	LF	Lead	3.610544845	97	16	
Industry Mine - Ash	LF	Mercury	0.000284536	97	92	
Industry Mine - Ash	LF	Selenium	0.052408247	97	64	
Industry Mine - Ash	LF	Thallium	0.016984286	70	12	
Industry Mine - FBC	LF	Antimony	0.017077778	9	4	
Industry Mine - FBC	LF	Arsenic	0.031111111	9	7	
Industry Mine - FBC	LF	Barium	9.515666667	9	0	
Industry Mine - FBC	LF	Boron	2.813888889	9	2	
Industry Mine - FBC	LF	Cadmium	0.015888889	9	7	
Industry Mine - FBC	LF	Cobalt	0.029333333	9	8	
Industry Mine - FBC	LF	Lead	0.051877778	9	6	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Industry Mine - FBC	LF	Mercury	0.000222222	9	8	
Industry Mine - FBC	LF	Selenium	0.080388889	9	4	
Industry Mine - FBC	LF	Thallium	0.002288889	9	6	
Key West - Ash	LF	Arsenic	0.005	1	1	
Key West - Ash	LF	Barium	1	2	0	
Key West - Ash	LF	Boron	0.2	1	0	
Key West - Ash	LF	Cadmium	0.07	1	0	
Key West - Ash	LF	Lead	0.4	1	0	
Key West - Ash	LF	Mercury	0.18	1	0	
Key West - Ash	LF	Selenium	0.005	1	1	
Keystone - Ash	LF	Aluminum	2.059	4	0	
Keystone - Ash	LF	Antimony	0.036	1	0	
Keystone - Ash	LF	Arsenic	0.30925	4	0	
Keystone - Ash	LF	Barium	0.40375	4	0	
Keystone - Ash	LF	Boron	0.72	1	0	
Keystone - Ash	LF	Cadmium	0.009625	4	1	
Keystone - Ash	LF	Cobalt	0.023	1	0	
Keystone - Ash	LF	Lead	0.045375	4	1	
Keystone - Ash	LF	Mercury	0.001	1	1	
Keystone - Ash	LF	Molybdenum	0.32	1	0	
Keystone - Ash	LF	Selenium	0.0525	4	2	
Keystone - Ash	LF	Thallium	0.083	1	0	
Keystone - Ash and Coal Refuse	LF	Aluminum	0.842	4	0	
Keystone - Ash and Coal Refuse	LF	Antimony	0.0015	2	2	
Keystone - Ash and Coal Refuse	LF	Arsenic	0.01875	4	4	
Keystone - Ash and Coal Refuse	LF	Barium	0.1925	4	0	
Keystone - Ash and Coal Refuse	LF	Boron	0.06	1	0	
Keystone - Ash and Coal Refuse	LF	Cadmium	0.00225	4	4	
Keystone - Ash and Coal Refuse	LF	Cobalt	0.022	1	0	
Keystone - Ash and Coal Refuse	LF	Lead	0.01875	4	4	
Keystone - Ash and Coal Refuse	LF	Mercury	0.001	1	1	
Keystone - Ash and Coal Refuse	LF	Molybdenum	0.01	2	2	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Keystone - Ash and Coal Refuse	LF	Selenium	0.02	4	4	
Keystone - Ash and Coal Refuse	LF	Thallium	0.028	1	0	
Kraft - Ash	LF	Arsenic	0.02	1	0	
Kraft - Ash	LF	Barium	0.3	1	0	
Kraft - Ash	LF	Cadmium	0.01	1	0	
Kraft - Ash	LF	Lead	0.04	1	0	
Kraft - Ash	LF	Selenium	0.04	1	0	
LIMB Site - Ash	LF	Aluminum	0.102894737	38	37	
LIMB Site - Ash	LF	Antimony	0.29	5	1	25
LIMB Site - Ash	LF	Arsenic	0.033594737	38	6	63
LIMB Site - Ash	LF	Barium	0.036552632	38	0	255
LIMB Site - Ash	LF	Boron	0.521842105	38	31	400
LIMB Site - Ash	LF	Cadmium	0.001031579	38	33	0.31
LIMB Site - Ash	LF	Cobalt	0.005131579	38	37	
LIMB Site - Ash	LF	Lead	0.012789474	38	25	14.5
LIMB Site - Ash	LF	Mercury	0.0001	2	2	
LIMB Site - Ash	LF	Molybdenum	1.527342105	38	1	2.5
LIMB Site - Ash	LF	Nitrate/Nitrite	26	2	0	
LIMB Site - Ash	LF	Selenium	0.0199	38	24	0.25
LIMB Site - Ash	LF	Thallium	0.05	5	5	
Little Sandy #10 Mine - Ash	LF	Aluminum	1.078	6	2	4541.666667
Little Sandy #10 Mine - Ash	LF	Arsenic	0.032336364	11	8	38.293
Little Sandy #10 Mine - Ash	LF	Barium	0.264454545	11	6	48.81
Little Sandy #10 Mine - Ash	LF	Boron	2.630909091	11	3	157.76
Little Sandy #10 Mine - Ash	LF	Cadmium	0.008290909	11	9	1.198
Little Sandy #10 Mine - Ash	LF	Lead	0.022009091	11	10	56.84
Little Sandy #10 Mine - Ash	LF	Mercury	0.000486364	11	10	0.24435
Little Sandy #10 Mine - Ash	LF	Molybdenum	0.177272727	11	5	6.354
Little Sandy #10 Mine - Ash	LF	Selenium	0.059527273	11	9	6.531
Lone Mtn - Ash	LF	Aluminum	28.615	2	0	
Lone Mtn - Ash	LF	Antimony	0.033	2	0	
Lone Mtn - Ash	LF	Arsenic	0.185	2	0	76
Lone Mtn - Ash	LF	Barium	0.167	2	0	1483.2
Lone Mtn - Ash	LF	Cadmium	0.572	2	0	11.86
Lone Mtn - Ash	LF	Cobalt	0.142	2	0	87.3
Lone Mtn - Ash	LF	Mercury	0.0019	1	0	
Lone Mtn - Ash	LF	Molybdenum	0.4295	2	0	
Lone Mtn - Ash	LF	Selenium	0.328	2	0	
LS - Ash and Coal Refuse	LF	Aluminum	1.18	7	0	
LS - Ash and Coal Refuse	LF	Antimony	0.0107	4	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
LS - Ash and Coal Refuse	LF	Arsenic	0.0104525	16	3	
LS - Ash and Coal Refuse	LF	Barium	0.13220625	16	0	
LS - Ash and Coal Refuse	LF	Boron	18.93125	16	0	
LS - Ash and Coal Refuse	LF	Cadmium	0.00148	16	15	
LS - Ash and Coal Refuse	LF	Cobalt	0.011125	4	0	
LS - Ash and Coal Refuse	LF	Lead	0.0025	16	16	
LS - Ash and Coal Refuse	LF	Mercury	0.00007	4	3	
LS - Ash and Coal Refuse	LF	Molybdenum	0.886875	16	0	
LS - Ash and Coal Refuse	LF	Nitrate/Nitrite	3.045	32	16	
LS - Ash and Coal Refuse	LF	Selenium	1.05343125	16	0	
LS - Ash and Coal Refuse	LF	Thallium	0.00185	8	8	
Martins Creek - Ash	LF	Aluminum	3.18335	20	2	114229.3889
Martins Creek - Ash	LF	Antimony	0.005021053	19	11	10.315
Martins Creek - Ash	LF	Arsenic	0.2314	20	1	50.50530556
Martins Creek - Ash	LF	Barium	0.1969	20	2	641.5466667
Martins Creek - Ash	LF	Boron	3.5089	20	1	304.1266667
Martins Creek - Ash	LF	Cadmium	0.0032	20	20	2.025
Martins Creek - Ash	LF	Cobalt	0.024722222	18	18	66.37611111
Martins Creek - Ash	LF	Lead	0.014	20	19	
Martins Creek - Ash	LF	Mercury	0.0001	19	19	
Martins Creek - Ash	LF	Molybdenum	0.195157895	19	10	
Martins Creek - Ash	LF	Nitrate/Nitrite	0.636428571	14	9	
Martins Creek - Ash	LF	Selenium	0.05717	20	8	4.043888889
Martins Creek - Ash	LF	Thallium	0.003263158	19	19	
McCloskey Site - FBC	LF	Aluminum	0.5	2	2	27450
McCloskey Site - FBC	LF	Arsenic	0.001	2	2	45.355
McCloskey Site - FBC	LF	Barium	0.1	2	2	32.55
McCloskey Site - FBC	LF	Boron	0.022	2	1	0.092
McCloskey Site - FBC	LF	Cadmium	0.0375	2	1	0.025
McCloskey Site - FBC	LF	Lead	0.05	2	2	50
McCloskey Site - FBC	LF	Mercury	0.25	2	2	0.4465
McCloskey Site - FBC	LF	Molybdenum	0.15	2	2	0.15
McCloskey Site - FBC	LF	Selenium	0.0515675	2	2	52.315
McDonough - Ash	LF	Arsenic	0.9	1	0	
McDonough - Ash	LF	Barium	0.5	1	0	
McDonough - Ash	LF	Cadmium	0.01	1	0	
McDonough - Ash	LF	Lead	0.04	1	0	
McDonough - Ash	LF	Selenium	0.2	1	0	
McIntosh - Ash	LF	Arsenic	0.09	1	0	
McIntosh - Ash	LF	Barium	0.2	1	0	
McIntosh - Ash	LF	Cadmium	0.6	1	0	
McIntosh - Ash	LF	Lead	0.03	1	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
McIntosh - Ash	LF	Selenium	0.03	1	0	
McKay Site - FBC	LF	Aluminum	0.105	2	0	30000
McKay Site - FBC	LF	Antimony	0.01	2	2	2.5
McKay Site - FBC	LF	Arsenic	0.025	2	2	51.5
McKay Site - FBC	LF	Barium	0.27	2	0	215
McKay Site - FBC	LF	Boron	0.265	2	0	41.5
McKay Site - FBC	LF	Cadmium	0.005	2	2	2.5
McKay Site - FBC	LF	Lead	0.03	2	1	49
McKay Site - FBC	LF	Mercury	0.0001	2	2	0.345
McKay Site - FBC	LF	Molybdenum	0.13	2	0	6.25
McKay Site - FBC	LF	Nitrate/Nitrite	0.0175	2	1	
McKay Site - FBC	LF	Selenium	0.0355	2	1	1
Miller - Ash	LF	Arsenic	1.3	1	0	18
Miller - Ash	LF	Barium	0.1	1	0	7140
Miller - Ash	LF	Cadmium	0.09	1	0	1.6
Miller - Ash	LF	Lead	0.002	1	0	38
Miller - Ash	LF	Selenium	0.03	1	0	
Miller Creek Mine - Ash	LF	Aluminum	4.78597619	42	4	22486.5969
Miller Creek Mine - Ash	LF	Arsenic	0.075817021	47	16	60.54551064
Miller Creek Mine - Ash	LF	Barium	0.147255319	47	0	87.49382979
Miller Creek Mine - Ash	LF	Boron	2.343829787	47	3	167.0508511
Miller Creek Mine - Ash	LF	Cadmium	0.009771277	47	31	1.850959894
Miller Creek Mine - Ash	LF	Lead	0.034382979	47	24	51.50851064
Miller Creek Mine - Ash	LF	Mercury	0.000255319	47	46	0.06780663
Miller Creek Mine - Ash	LF	Molybdenum	0.166808511	47	17	9.819680851
Miller Creek Mine - Ash	LF	Selenium	0.047102128	47	23	6.492617021
Mine 26 - Ash	LF	Antimony	0.0125	6	6	
Mine 26 - Ash	LF	Arsenic	0.022333333	9	8	
Mine 26 - Ash	LF	Barium	0.388111111	9	1	
Mine 26 - Ash	LF	Boron	9.266666667	9	0	
Mine 26 - Ash	LF	Cadmium	0.008555556	9	4	
Mine 26 - Ash	LF	Cobalt	0.021744444	9	5	
Mine 26 - Ash	LF	Lead	0.148111111	9	6	
Mine 26 - Ash	LF	Mercury	0.0003	9	9	
Mine 26 - Ash	LF	Selenium	0.026388889	9	6	
Mine 26 - Ash	LF	Thallium	0.006833333	6	5	
Mine 26 - Ash and Coal Refuse	LF	Antimony	0.01	2	2	
Mine 26 - Ash and Coal Refuse	LF	Arsenic	0.054285714	7	5	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Mine 26 - Ash and Coal Refuse	LF	Barium	0.615714286	7	0	
Mine 26 - Ash and Coal Refuse	LF	Boron	3.504285714	7	0	
Mine 26 - Ash and Coal Refuse	LF	Cadmium	0.010142857	7	4	
Mine 26 - Ash and Coal Refuse	LF	Cobalt	0.032857143	7	2	
Mine 26 - Ash and Coal Refuse	LF	Lead	0.047142857	7	4	
Mine 26 - Ash and Coal Refuse	LF	Mercury	0.0001	7	7	
Mine 26 - Ash and Coal Refuse	LF	Selenium	0.02	7	7	
Mine 26 - Ash and Coal Refuse	LF	Thallium	0.005	2	2	
Mine 26 - FBC	LF	Arsenic	0.03	1	1	
Mine 26 - FBC	LF	Barium	0.51	1	0	
Mine 26 - FBC	LF	Boron	1.3	1	0	
Mine 26 - FBC	LF	Cadmium	0.0025	1	1	
Mine 26 - FBC	LF	Cobalt	0.005	1	1	
Mine 26 - FBC	LF	Lead	0.01	1	1	
Mine 26 - FBC	LF	Mercury	0.0001	1	1	
Mine 26 - FBC	LF	Selenium	0.08	1	0	
Mitchell - Ash	LF	Arsenic	1.3	1	0	
Mitchell - Ash	LF	Barium	0.3	1	0	
Mitchell - Ash	LF	Cadmium	0.01	1	0	
Mitchell - Ash	LF	Lead	0.06	1	0	
Mitchell - Ash	LF	Selenium	0.06	1	0	
MO - Ash and Coal Refuse	LF	Aluminum	4.49	2	0	
MO - Ash and Coal Refuse	LF	Antimony	0.0125	2	0	
MO - Ash and Coal Refuse	LF	Arsenic	0.2855	2	0	
MO - Ash and Coal Refuse	LF	Barium	1.845	2	0	
MO - Ash and Coal Refuse	LF	Boron	0.219	2	0	
MO - Ash and Coal Refuse	LF	Cadmium	0.006	2	0	
MO - Ash and Coal Refuse	LF	Cobalt	0.012	2	0	
MO - Ash and Coal Refuse	LF	Lead	0.0065	2	0	
MO - Ash and Coal Refuse	LF	Mercury	0.00005	4	4	
MO - Ash and Coal Refuse	LF	Selenium	0.1312	2	0	
MO - Ash and Coal Refuse	LF	Thallium	0.01415	2	0	
Murdock Mine - Ash	LF	Antimony	0.0076875	8	8	
Murdock Mine - Ash	LF	Arsenic	0.0080875	8	6	
Murdock Mine - Ash	LF	Barium	0.258625	8	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Murdock Mine - Ash	LF	Boron	9.38775	8	0	
Murdock Mine - Ash	LF	Cadmium	0.0458	8	2	
Murdock Mine - Ash	LF	Cobalt	0.0225625	8	2	
Murdock Mine - Ash	LF	Lead	0.00555	8	2	
Murdock Mine - Ash	LF	Mercury	0.0004375	8	8	
Murdock Mine - Ash	LF	Selenium	0.0053875	8	4	
Murdock Mine - Ash	LF	Thallium	0.02325	8	2	
Murdock Mine - FBC	LF	Antimony	0.004	3	3	
Murdock Mine - FBC	LF	Arsenic	0.005	3	3	
Murdock Mine - FBC	LF	Barium	0.368333333	3	0	
Murdock Mine - FBC	LF	Boron	0.436666667	3	0	
Murdock Mine - FBC	LF	Cadmium	0.0015	3	3	
Murdock Mine - FBC	LF	Cobalt	0.0025	3	3	
Murdock Mine - FBC	LF	Lead	0.0015	3	3	
Murdock Mine - FBC	LF	Mercury	0.0004	3	3	
Murdock Mine - FBC	LF	Selenium	0.003533333	3	2	
Murdock Mine - FBC	LF	Thallium	0.005	3	3	
Nepco - FBC	LF	Arsenic	0.025	2	2	21
Nepco - FBC	LF	Cadmium	0.01	1	0	0.5
Nepco - FBC	LF	Lead	0.025	2	2	39
Nepco - FBC	LF	Mercury	0.0002	2	2	0.01
Nepco - FBC	LF	Selenium	0.05	2	2	12.6
No. 1 Contracting Corp - FBC	LF	Aluminum	0.935	2	0	
No. 1 Contracting Corp - FBC	LF	Antimony	0.018	1	0	
No. 1 Contracting Corp - FBC	LF	Arsenic	0.046	2	0	
No. 1 Contracting Corp - FBC	LF	Barium	0.1315	2	0	
No. 1 Contracting Corp - FBC	LF	Boron	0.05	1	0	
No. 1 Contracting Corp - FBC	LF	Cadmium	0.005	1	0	
No. 1 Contracting Corp - FBC	LF	Lead	0.06	1	0	
No. 1 Contracting Corp - FBC	LF	Mercury	0.0002	1	0	
No. 1 Contracting Corp - FBC	LF	Molybdenum	0.105	2	0	
No. 1 Contracting Corp - FBC	LF	Selenium	0.1395	2	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Northampton40000201 - Ash	LF	Aluminum	0.38	1	0	24500
Northampton40000201 - Ash	LF	Antimony	0.01	1	0	20
Northampton40000201 - Ash	LF	Arsenic	0.005	1	0	40.6
Northampton40000201 - Ash	LF	Barium	0.21	1	0	242
Northampton40000201 - Ash	LF	Boron	0.2	1	0	17.3
Northampton40000201 - Ash	LF	Cadmium	0.012	1	0	0.5
Northampton40000201 - Ash	LF	Lead	0.1	1	0	18
Northampton40000201 - Ash	LF	Mercury	0.0002	1	0	0.535
Northampton40000201 - Ash	LF	Molybdenum	0.1	1	0	10
Northampton40000201 - Ash	LF	Selenium	0.015	1	0	8.9
Nucla - FBC	LF	Aluminum	0.1	2	2	110050
Nucla - FBC	LF	Arsenic	0.0025	4	4	7.4
Nucla - FBC	LF	Barium	0.08	2	1	190
Nucla - FBC	LF	Boron	0.485	2	1	57.5
Nucla - FBC	LF	Cadmium	0.00055	2	2	1.95
Nucla - FBC	LF	Cobalt	0.005	2	2	10
Nucla - FBC	LF	Lead	0.0016	2	1	35.5
Nucla - FBC	LF	Mercury	0.0001	2	2	
Nucla - FBC	LF	Molybdenum	0.2045	2	0	83
Nucla - FBC	LF	Nitrate/Nitrite	0.1125	2	2	
Nucla - FBC	LF	Selenium	0.00485	2	1	9.35
Nucla2 - FBC	LF	Aluminum	7.18	3	0	100000
Nucla2 - FBC	LF	Antimony	0.1	6	6	46
Nucla2 - FBC	LF	Arsenic	0.00375	6	5	27.93333333
Nucla2 - FBC	LF	Barium	0.093	3	0	246
Nucla2 - FBC	LF	Boron	3.1	3	1	69.16666667
Nucla2 - FBC	LF	Cadmium	0.000475	6	4	0.263333333
Nucla2 - FBC	LF	Cobalt	0.012	3	1	6.1
Nucla2 - FBC	LF	Lead	0.0062	3	0	8.296666667
Nucla2 - FBC	LF	Mercury	0.000566667	6	5	0.214166667
Nucla2 - FBC	LF	Molybdenum	0.303333333	3	0	3.316666667
Nucla2 - FBC	LF	Nitrate/Nitrite	6.591666667	6	4	
Nucla2 - FBC	LF	Selenium	0.048666667	6	2	1.395
Nucla2 - FBC	LF	Thallium	0.05	3	3	6.416666667

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
OK - Ash	LF	Aluminum	11.895	2	0	
OK - Ash	LF	Antimony	0.001575	2	1	
OK - Ash	LF	Arsenic	0.003225	2	1	
OK - Ash	LF	Barium	0.686	2	0	
OK - Ash	LF	Boron	2.68	2	0	
OK - Ash	LF	Cadmium	0.00027	2	1	
OK - Ash	LF	Cobalt	0.00745	2	0	
OK - Ash	LF	Lead	0.00355	2	0	
OK - Ash	LF	Mercury	0.0001	2	1	
OK - Ash	LF	Selenium	0.037	2	0	
OK - Ash	LF	Thallium	0.00185	4	4	
P4 - Ash	LF	Aluminum	6.2196875	8	0	
P4 - Ash	LF	Antimony	0.00105	4	4	
P4 - Ash	LF	Arsenic	0.00420375	8	5	
P4 - Ash	LF	Barium	0.254375	8	0	
P4 - Ash	LF	Boron	1.142697917	8	0	
P4 - Ash	LF	Cadmium	0.00125	8	8	
P4 - Ash	LF	Cobalt	0.00315	2	0	
P4 - Ash	LF	Lead	0.0025	8	8	
P4 - Ash	LF	Mercury	0.00005	4	4	
P4 - Ash	LF	Molybdenum	0.2114375	8	4	
P4 - Ash	LF	Nitrate/Nitrite	1.92075	16	8	
P4 - Ash	LF	Selenium	0.01	8	8	
P4 - Ash	LF	Thallium	0.002775	2	2	
PA - Ash	LF	Aluminum	26.16153846	13	0	
PA - Ash	LF	Antimony	0.0031	2	0	
PA - Ash	LF	Arsenic	0.005991923	13	9	
PA - Ash	LF	Barium	1.043838462	13	0	
PA - Ash	LF	Boron	0.736153846	13	0	
PA - Ash	LF	Cadmium	0.001758462	13	12	
PA - Ash	LF	Cobalt	0.001915	2	2	
PA - Ash	LF	Lead	0.005993077	13	10	
PA - Ash	LF	Mercury	0.000175	2	0	
PA - Ash	LF	Molybdenum	0.138461538	13	4	
PA - Ash	LF	Nitrate/Nitrite	2.544596154	26	15	
PA - Ash	LF	Selenium	0.084376923	13	5	
PA - Ash	LF	Thallium	0.00196	4	4	
Pitt - FBC	LF	Antimony	0.0219	1	0	
Pitt - FBC	LF	Arsenic	0.05	1	1	
Pitt - FBC	LF	Barium	1.167333333	3	1	
Pitt - FBC	LF	Cadmium	0.033333333	3	3	
Pitt - FBC	LF	Lead	0.183333333	3	3	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Pitt - FBC	LF	Mercury	0.005	1	1	
Pitt - FBC	LF	Selenium	0.05	1	1	
Pitt - FBC	LF	Thallium	0.0025	3	3	
Plant 10 - FBC	LF	Arsenic	0.14875	4	0	71.3
Plant 10 - FBC	LF	Cadmium	0.05425	4	1	2.418181818
Plant 10 - FBC	LF	Lead	0.2965	4	1	39.63636364
Plant 10 - FBC	LF	Mercury	0.05005	4	4	1.174
Plant 10 - FBC	LF	Selenium	0.1285	4	0	4.011818182
Plant 12 - FBC	LF	Arsenic	0.004125	8	4	98.62222222
Plant 12 - FBC	LF	Cadmium	0.02	8	8	2.188888889
Plant 12 - FBC	LF	Lead	0.28375	8	2	47.83333333
Plant 12 - FBC	LF	Mercury	0.0004	8	8	1.047777778
Plant 12 - FBC	LF	Selenium	0.006125	8	8	4.263888889
Plant 8 - FBC	LF	Arsenic	0.019868421	19	18	42.04210526
Plant 8 - FBC	LF	Cadmium	0.016826923	52	43	2.288947368
Plant 8 - FBC	LF	Lead	0.007211538	52	37	27.62105263
Plant 8 - FBC	LF	Mercury	0.000289474	19	19	0.065789474
Plant 8 - FBC	LF	Selenium	0.053026316	19	9	33.02263158
Plant 9 - FBC	LF	Arsenic	0.058666667	3	0	2.8
Plant 9 - FBC	LF	Lead	0.105454545	11	8	57.67142857
Plant 9 - FBC	LF	Mercury	0.00025	11	11	0.604285714
Plant 9 - FBC	LF	Selenium	0.065333333	3	0	5.115714286
Portland - Ash	LF	Aluminum	2.648555556	9	0	
Portland - Ash	LF	Antimony	0.075	2	2	
Portland - Ash	LF	Arsenic	0.178666667	9	6	
Portland - Ash	LF	Barium	0.28475	8	0	
Portland - Ash	LF	Boron	4.799333333	3	0	
Portland - Ash	LF	Cadmium	0.006	9	7	
Portland - Ash	LF	Cobalt	0.014	2	1	
Portland - Ash	LF	Lead	0.058333333	9	8	
Portland - Ash	LF	Mercury	0.001	4	4	
Portland - Ash	LF	Molybdenum	0.178666667	3	1	
Portland - Ash	LF	Selenium	0.25625	4	4	
Portland - Ash	LF	Thallium	0.005	4	4	
PP - Ash	LF	Aluminum	2.422	2	0	
PP - Ash	LF	Antimony	0.00245	2	0	
PP - Ash	LF	Arsenic	0.0273375	2	1	
PP - Ash	LF	Barium	0.2435	2	0	
PP - Ash	LF	Boron	6.605	2	0	
PP - Ash	LF	Cadmium	0.0023975	2	1	
PP - Ash	LF	Cobalt	0.0049575	2	1	
PP - Ash	LF	Lead	0.001155	2	1	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
PP - Ash	LF	Mercury	0.00028	2	0	
PP - Ash	LF	Selenium	0.0364	2	0	
PP - Ash	LF	Thallium	0.01518	2	1	
Revloc Site - FBC	LF	Aluminum	0.58	2	1	
Revloc Site - FBC	LF	Antimony	0.002	2	2	
Revloc Site - FBC	LF	Arsenic	0.002	2	1	
Revloc Site - FBC	LF	Barium	0.44	2	2	
Revloc Site - FBC	LF	Boron	0.2585	2	1	
Revloc Site - FBC	LF	Cadmium	0.02	2	2	
Revloc Site - FBC	LF	Cobalt	0.0825	2	1	
Revloc Site - FBC	LF	Lead	0.25	2	0	
Revloc Site - FBC	LF	Mercury	0.0005	2	2	
Revloc Site - FBC	LF	Molybdenum	0.0545	2	1	
Revloc Site - FBC	LF	Selenium	0.0025	2	1	
Scherer - Ash	LF	Arsenic	0.01	1	0	
Scherer - Ash	LF	Barium	0.7	1	0	
Scherer - Ash	LF	Cadmium	0.001	1	0	
Scherer - Ash	LF	Lead	0.001	1	0	
Scherer - Ash	LF	Selenium	0.06	1	0	
Scholz - Ash	LF	Arsenic	0.02	1	0	
Scholz - Ash	LF	Barium	0.2	1	0	
Scholz - Ash	LF	Cadmium	0.04	1	0	
Scholz - Ash	LF	Lead	0.04	1	0	
Scholz - Ash	LF	Selenium	0.02	1	0	
Scrubgrass - FBC	LF	Arsenic	0.025	2	2	59
Scrubgrass - FBC	LF	Cadmium	0.0025	1	0	0.7
Scrubgrass - FBC	LF	Lead	0.025	2	2	50
Scrubgrass - FBC	LF	Mercury	0.0002	2	2	0.01
Scrubgrass - FBC	LF	Selenium	0.05	2	2	21.7
Seward - Ash	LF	Aluminum	2.965	2	0	
Seward - Ash	LF	Antimony	0.075	2	2	
Seward - Ash	LF	Arsenic	0.288666667	3	2	
Seward - Ash	LF	Barium	0.473333333	3	0	
Seward - Ash	LF	Boron	0.57	1	0	
Seward - Ash	LF	Cadmium	0.005833333	3	1	
Seward - Ash	LF	Cobalt	0.014	1	0	
Seward - Ash	LF	Lead	0.1875	1	1	
Seward - Ash	LF	Mercury	0.003733333	3	3	
Seward - Ash	LF	Molybdenum	0.53	1	0	
Seward - Ash	LF	Selenium	0.196666667	3	2	
Seward - Ash	LF	Thallium	0.012	1	0	
Shawnee - FBC	LF	Aluminum	0.231	5	3	38240

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Shawnee - FBC	LF	Antimony	0.296	5	2	15.6
Shawnee - FBC	LF	Arsenic	0.219	10	6	17.3
Shawnee - FBC	LF	Barium	2.001	10	0	799.4
Shawnee - FBC	LF	Boron	0.97	5	3	116.2
Shawnee - FBC	LF	Cadmium	0.005555	10	7	0.622
Shawnee - FBC	LF	Cobalt	0.07	5	2	2.75
Shawnee - FBC	LF	Lead	0.0897	10	5	6.4
Shawnee - FBC	LF	Mercury	0.00029	10	8	0.365
Shawnee - FBC	LF	Molybdenum	0.382	5	0	6.4
Shawnee - FBC	LF	Nitrate/Nitrite	3.786666667	8	4	
Shawnee - FBC	LF	Selenium	0.13005	10	6	0.73
Shawnee - FBC	LF	Thallium	0.197	5	3	8.9
Shawville - Ash	LF	Aluminum	2.0958	5	0	
Shawville - Ash	LF	Antimony	0.075	2	2	
Shawville - Ash	LF	Arsenic	0.4384	5	1	
Shawville - Ash	LF	Barium	0.2172	5	0	
Shawville - Ash	LF	Boron	0.56	1	0	
Shawville - Ash	LF	Cadmium	0.0059	5	2	
Shawville - Ash	LF	Cobalt	0.021	1	0	
Shawville - Ash	LF	Lead	0.1875	1	1	
Shawville - Ash	LF	Mercury	0.001	2	2	
Shawville - Ash	LF	Molybdenum	0.09	1	0	
Shawville - Ash	LF	Selenium	0.191	5	2	
Shawville - Ash	LF	Thallium	0.005	2	2	
Sibley Quarry - Ash	LF	Aluminum	0.6	4	4	
Sibley Quarry - Ash	LF	Arsenic	0.018	4	0	
Sibley Quarry - Ash	LF	Barium	0.265	4	4	
Sibley Quarry - Ash	LF	Cadmium	0.00114125	4	2	
Sibley Quarry - Ash	LF	Lead	0.00305	4	4	
Sibley Quarry - Ash	LF	Mercury	0.0001	4	4	
Sibley Quarry - Ash	LF	Molybdenum	0.725	3	1	
Sibley Quarry - Ash	LF	Selenium	0.18425	4	1	
Silverton - Ash	LF	Aluminum	3.1	1	0	16870
Silverton - Ash	LF	Arsenic	0.375	2	0	48.5
Silverton - Ash	LF	Barium	1.7	1	0	181.5
Silverton - Ash	LF	Boron	0.22	1	0	20.5
Silverton - Ash	LF	Lead	0.23	1	0	29.5
Silverton - Ash	LF	Molybdenum	0.1	1	0	5
Silverton - Ash	LF	Selenium	0.12	2	0	6.7
Smith - Ash	LF	Arsenic	0.02	1	0	
Smith - Ash	LF	Barium	0.2	1	0	
Smith - Ash	LF	Cadmium	0.04	1	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Smith - Ash	LF	Lead	0.01	1	0	
Smith - Ash	LF	Selenium	0.01	1	0	
SW - Ash	LF	Arsenic	0.006679487	195	53	29.495189
SW - Ash	LF	Barium	0.81082716	243	0	2538.862069
SW - Ash	LF	Cadmium	0.003400769	195	47	1.230670103
SW - Ash	LF	Lead	0.001570707	99	97	35.39886598
SW - Ash	LF	Mercury	0.000217677	99	98	0.039255034
SW - Ash	LF	Selenium	0.003534884	172	46	0.6
SX - Ash	LF	Aluminum	1.862	2	0	
SX - Ash	LF	Antimony	0.003275	2	1	
SX - Ash	LF	Arsenic	0.0365	2	0	
SX - Ash	LF	Barium	0.959	2	0	
SX - Ash	LF	Boron	4.5223	2	0	
SX - Ash	LF	Cadmium	0.04425	2	0	
SX - Ash	LF	Cobalt	0.0167	2	0	
SX - Ash	LF	Lead	0.00675	2	0	
SX - Ash	LF	Mercury	0.00005	4	4	
SX - Ash	LF	Selenium	0.048725	2	1	
SX - Ash	LF	Thallium	0.013625	2	1	
Tidd - FBC	LF	Aluminum	0.105	3	1	
Tidd - FBC	LF	Antimony	0.03	5	5	
Tidd - FBC	LF	Arsenic	0.028333333	3	2	
Tidd - FBC	LF	Barium	0.184	2	0	
Tidd - FBC	LF	Boron	0.82	3	0	
Tidd - FBC	LF	Cadmium	0.0015	3	3	
Tidd - FBC	LF	Cobalt	0.021	3	0	
Tidd - FBC	LF	Lead	0.015833333	3	3	
Tidd - FBC	LF	Mercury	0.006733333	3	3	
Tidd - FBC	LF	Molybdenum	0.082	3	0	
Tidd - FBC	LF	Selenium	0.101666667	3	2	
Titus - Ash	LF	Aluminum	4.4135	4	0	
Titus - Ash	LF	Antimony	0.04375	4	4	
Titus - Ash	LF	Arsenic	0.346	2	1	
Titus - Ash	LF	Barium	0.3	4	0	
Titus - Ash	LF	Boron	7.345	2	0	
Titus - Ash	LF	Cadmium	0.0115	4	0	
Titus - Ash	LF	Cobalt	0.027	2	0	
Titus - Ash	LF	Lead	0.19375	2	2	
Titus - Ash	LF	Mercury	0.001	2	2	
Titus - Ash	LF	Molybdenum	0.34	2	0	
Titus - Ash	LF	Selenium	0.144	4	3	
Titus - Ash	LF	Thallium	0.01	2	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Tracy Vein Slope - Ash	LF	Aluminum	0.533833333	6	0	11090
Tracy Vein Slope - Ash	LF	Antimony	0.05	5	0	24.215
Tracy Vein Slope - Ash	LF	Arsenic	0.065166667	6	0	61.33333333
Tracy Vein Slope - Ash	LF	Barium	0.148833333	6	0	99.31666667
Tracy Vein Slope - Ash	LF	Boron	1.4486	5	0	122.4333333
Tracy Vein Slope - Ash	LF	Cadmium	0.044833333	6	0	1.070166667
Tracy Vein Slope - Ash	LF	Lead	0.075	6	0	18.90833333
Tracy Vein Slope - Ash	LF	Mercury	0.001	2	0	1.5888
Tracy Vein Slope - Ash	LF	Molybdenum	0.1662	5	0	7.721666667
Tracy Vein Slope - Ash	LF	Selenium	0.0524	5	0	8.608
Tracy Vein Slope - FBC	LF	Aluminum	1.32	1	0	7240
Tracy Vein Slope - FBC	LF	Arsenic	0.052	1	0	6.97
Tracy Vein Slope - FBC	LF	Barium	0.056	1	0	68.9
Tracy Vein Slope - FBC	LF	Boron	0.043	1	0	7.43
Tracy Vein Slope - FBC	LF	Molybdenum	0.027	1	0	0.84
Tracy Vein Slope - FBC	LF	Selenium	0.039	1	0	3.22
UAPP - Ash	LF	Arsenic	0.0025	2	2	
UAPP - Ash	LF	Barium	0.4	2	1	
UAPP - Ash	LF	Cadmium	0.04	2	2	
UAPP - Ash	LF	Lead	0.1	2	2	
UAPP - Ash	LF	Mercury	0.025	2	2	
UAPP - Ash	LF	Selenium	0.00275	2	1	
Universal - Ash	LF	Aluminum	2.057777778	9	0	6000.222222
Universal - Ash	LF	Arsenic	0.277818182	11	2	41.50909091
Universal - Ash	LF	Barium	0.090181818	11	1	71
Universal - Ash	LF	Boron	2.754545455	11	0	180.2954545
Universal - Ash	LF	Cadmium	0.003227273	11	9	2.115909091
Universal - Ash	LF	Lead	0.022145455	11	7	33.00909091
Universal - Ash	LF	Mercury	0.000386364	11	11	0.137272727
Universal - Ash	LF	Molybdenum	0.134363636	11	1	3.554545455
Universal - Ash	LF	Selenium	0.160090909	11	2	7.106363636
Wansley - Ash	LF	Arsenic	0.05	1	0	
Wansley - Ash	LF	Barium	0.2	1	0	
Wansley - Ash	LF	Cadmium	0.09	1	0	
Wansley - Ash	LF	Lead	0.02	1	0	
Wansley - Ash	LF	Selenium	0.06	1	0	
WEPCO CALEDONIA LANDFILL - Ash	LF	Barium	0.225	2	0	
WEPCO CALEDONIA LANDFILL - Ash	LF	Boron	16.90454545	22	0	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
WEPCO CALEDONIA LANDFILL - Ash	LF	Cadmium	0.000045	3	3	
WEPCO CALEDONIA LANDFILL - Ash	LF	Lead	0.003566667	3	3	
WEPCO CALEDONIA LANDFILL - Ash	LF	Molybdenum	0.77500575	4	3	
WEPCO CALEDONIA LANDFILL - Ash	LF	Selenium	0.046794118	34	0	
WEPCO HWY 32 LANDFILL - Ash	LF	Boron	83.41666667	12	0	
WEPCO HWY 32 LANDFILL - Ash	LF	Selenium	0.006675	12	4	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Arsenic	0.0055	2	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Barium	0.1195	2	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Boron	14.02134483	29	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Cadmium	0.010266667	3	1	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Lead	0.00625	2	1	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Mercury	0.0002	1	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Molybdenum	0.000022375	4	4	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Nitrate/Nitrite	1.866666667	3	0	
WEPCO SYSTEMS CONTROL CENTER A - Ash	LF	Selenium	0.06332275	28	0	
Wilton Site - Ash	LF	Aluminum	3	1	0	
Wilton Site - Ash	LF	Arsenic	0.027	1	0	
Wilton Site - Ash	LF	Barium	0.51	1	0	
Wilton Site - Ash	LF	Boron	25	1	0	
Wilton Site - Ash	LF	Cadmium	0.0025	2	2	
Wilton Site - Ash	LF	Lead	0.0025	2	2	
Wilton Site - Ash	LF	Mercury	0.001	2	2	
Wilton Site - Ash	LF	Molybdenum	0.34	1	0	

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CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
Wilton Site - Ash	LF	Nitrate/Nitrite	0.5	1	1	
Wilton Site - Ash	LF	Selenium	0.09	1	0	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Arsenic	0.0014	3	2	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Barium	0.183025	4	1	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Boron	6.363333333	21	1	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Cadmium	0.0047595	8	0	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Lead	0.00668375	8	0	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Mercury	0.000082	5	5	
WIS PUBLIC SERV CORP-WESTON AS - Ash	LF	Selenium	0.011077619	21	1	
Yates1 - Ash	LF	Arsenic	0.1	1	0	
Yates1 - Ash	LF	Barium	0.3	1	0	
Yates1 - Ash	LF	Cadmium	0.02	1	0	
Yates1 - Ash	LF	Lead	0.05	1	0	
Yates1 - Ash	LF	Selenium	0.02	1	0	
Yates2 - Ash	LF	Arsenic	0.09	1	0	
Yates2 - Ash	LF	Barium	0.2	1	0	
Yates2 - Ash	LF	Cadmium	0.02	1	0	
Yates2 - Ash	LF	Lead	0.03	1	0	
Yates2 - Ash	LF	Selenium	0.05	1	0	
AP - Ash	SI	Aluminum	0.553384615	13	0	
AP - Ash	SI	Antimony	0.01	1	1	
AP - Ash	SI	Arsenic	0.070933333	15	0	
AP - Ash	SI	Barium	0.063066667	15	1	
AP - Ash	SI	Boron	12.50986667	15	0	
AP - Ash	SI	Cadmium	0.001042857	14	7	
AP - Ash	SI	Cobalt	0.01	1	1	
AP - Ash	SI	Lead	0.001723333	15	14	
AP - Ash	SI	Molybdenum	0.486733333	15	2	
AP - Ash	SI	Nitrate/Nitrite	0.254809524	29	22	
AP - Ash	SI	Selenium	0.044326667	15	1	
AP - Ash	SI	Thallium	0.0025	1	1	
BR - Ash and Coal Refuse	SI	Aluminum	89.12777778	18	0	
BR - Ash and Coal Refuse	SI	Arsenic	0.775383333	15	4	
BR - Ash and Coal Refuse	SI	Barium	0.188055556	18	14	
BR - Ash and Coal Refuse	SI	Boron	3.857694444	18	2	
BR - Ash and Coal Refuse	SI	Cadmium	0.175	18	7	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
BR - Ash and Coal Refuse	SI	Cobalt	0.204722222	18	11	
BR - Ash and Coal Refuse	SI	Molybdenum	0.5	18	18	
C - Ash	SI	Aluminum	4.192307692	13	0	
C - Ash	SI	Antimony	0.07	10	10	
C - Ash	SI	Arsenic	0.15	10	0	
C - Ash	SI	Barium	0.113769231	13	0	
C - Ash	SI	Boron	10.96428571	14	0	
C - Ash	SI	Cadmium	0.0025	10	10	
C - Ash	SI	Cobalt	0.005	10	10	
C - Ash	SI	Lead	0.00229	10	5	
C - Ash	SI	Molybdenum	0.585384615	13	0	
C - Ash	SI	Nitrate/Nitrite	10.85474359	16	3	
C - Ash	SI	Selenium	0.0175	10	2	
C - Ash	SI	Thallium	0.05	10	10	
CADK - Ash	SI	Aluminum	0.165	2	0	
CADK - Ash	SI	Arsenic	0.0075	2	2	
CADK - Ash	SI	Barium	0.02	2	2	
CADK - Ash	SI	Boron	60.05	2	0	
CADK - Ash	SI	Cadmium	0.001	2	2	
CADK - Ash	SI	Lead	0.1	2	2	
CADK - Ash	SI	Molybdenum	1.165	2	0	
CADK - Ash	SI	Nitrate/Nitrite	11.135	4	0	
CADK - Ash	SI	Selenium	0.125	2	0	
CASJ - Ash	SI	Aluminum	0.1108	5	4	
CASJ - Ash	SI	Arsenic	5.37225	4	0	
CASJ - Ash	SI	Barium	0.0214	5	2	
CASJ - Ash	SI	Boron	46.02	5	0	
CASJ - Ash	SI	Cadmium	0.0156	5	3	
CASJ - Ash	SI	Lead	0.21	5	4	
CASJ - Ash	SI	Molybdenum	0.13	5	5	
CASJ - Ash	SI	Nitrate/Nitrite	1.882	10	8	
CASJ - Ash	SI	Selenium	0.40575	4	0	
CATT - Ash	SI	Aluminum	0.28	2	0	
CATT - Ash	SI	Arsenic	0.206	2	0	
CATT - Ash	SI	Barium	0.085	2	0	
CATT - Ash	SI	Boron	110.5	2	0	
CATT - Ash	SI	Cadmium	0.002	2	1	
CATT - Ash	SI	Lead	0.2275	2	0	
CATT - Ash	SI	Molybdenum	0.655	2	0	
CATT - Ash	SI	Nitrate/Nitrite	0.01	2	0	
CATT - Ash	SI	Selenium	1.025	2	0	
CL - Ash and Coal Refuse	SI	Aluminum	4.680970556	30	2	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
CL - Ash and Coal Refuse	SI	Arsenic	0.493663408	30	2	
CL - Ash and Coal Refuse	SI	Barium	0.550251717	30	0	
CL - Ash and Coal Refuse	SI	Boron	1.092075	30	0	
CL - Ash and Coal Refuse	SI	Cadmium	0.001680507	30	27	
CL - Ash and Coal Refuse	SI	Lead	0.003384333	30	29	
CL - Ash and Coal Refuse	SI	Molybdenum	0.377590556	30	0	
CL - Ash and Coal Refuse	SI	Nitrate/Nitrite	0.6303	60	13	
CL - Ash and Coal Refuse	SI	Selenium	0.147525085	30	9	
CY - Ash	SI	Aluminum	6.0975	4	0	
CY - Ash	SI	Arsenic	0.1975	4	0	
CY - Ash	SI	Barium	0.179725	4	0	
CY - Ash	SI	Boron	0.025	4	4	
CY - Ash	SI	Cadmium	0.0040625	4	4	
CY - Ash	SI	Lead	0.008125	4	4	
CY - Ash	SI	Molybdenum	0.655	4	0	
CY - Ash	SI	Nitrate/Nitrite	750.2625	8	5	
CY - Ash	SI	Selenium	0.086575	4	1	
FC - Ash and Coal Refuse	SI	Aluminum	11.433	10	0	
FC - Ash and Coal Refuse	SI	Arsenic	0.00752	10	8	
FC - Ash and Coal Refuse	SI	Barium	0.14918	10	0	
FC - Ash and Coal Refuse	SI	Boron	0.7445	10	1	
FC - Ash and Coal Refuse	SI	Cadmium	0.001956	10	9	
FC - Ash and Coal Refuse	SI	Lead	0.0025	10	10	
FC - Ash and Coal Refuse	SI	Molybdenum	0.2275	10	10	
FC - Ash and Coal Refuse	SI	Nitrate/Nitrite	0.2	20	20	
FC - Ash and Coal Refuse	SI	Selenium	0.02174	10	0	
HA - Ash	SI	Aluminum	2.830833333	9	2	
HA - Ash	SI	Arsenic	0.086774333	9	2	
HA - Ash	SI	Barium	0.471945556	9	0	
HA - Ash	SI	Boron	2.283583333	9	0	
HA - Ash	SI	Cadmium	0.00125	9	9	
HA - Ash	SI	Lead	0.003503333	9	8	
HA - Ash	SI	Molybdenum	0.107333333	9	4	
HA - Ash	SI	Nitrate/Nitrite	1.968222222	18	10	
HA - Ash	SI	Selenium	0.01	9	9	
HA - Ash and Coal Refuse	SI	Aluminum	0.65	1	0	
HA - Ash and Coal Refuse	SI	Arsenic	0.18	1	0	
HA - Ash and Coal Refuse	SI	Barium	0.11	1	0	
HA - Ash and Coal Refuse	SI	Boron	1.7	1	0	
HA - Ash and Coal Refuse	SI	Cadmium	0.0025	1	1	
HA - Ash and Coal Refuse	SI	Lead	0.025	1	1	
HA - Ash and Coal Refuse	SI	Mercury	0.00025	1	1	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
HA - Ash and Coal Refuse	SI	Molybdenum	0.075	1	1	
HA - Ash and Coal Refuse	SI	Selenium	0.0025	1	1	
L - Ash	SI	Aluminum	0.015	2	2	
L - Ash	SI	Barium	0.001	2	2	
L - Ash	SI	Boron	0.62	2	0	
L - Ash	SI	Cadmium	0.001	2	2	
L - Ash	SI	Molybdenum	0.1675	2	1	
MO - Ash	SI	Aluminum	0.894458333	6	0	
MO - Ash	SI	Arsenic	0.011755993	6	3	
MO - Ash	SI	Barium	0.019379487	6	0	
MO - Ash	SI	Boron	0.085041667	6	2	
MO - Ash	SI	Cadmium	0.00125	6	6	
MO - Ash	SI	Lead	0.003666667	6	5	
MO - Ash	SI	Molybdenum	0.928770833	6	3	
MO - Ash	SI	Nitrate/Nitrite	0.1205	12	10	
MO - Ash	SI	Selenium	0.005	6	6	
MO - Ash and Coal Refuse	SI	Aluminum	296.2888026	19	6	
MO - Ash and Coal Refuse	SI	Arsenic	11.67554177	20	0	
MO - Ash and Coal Refuse	SI	Barium	0.039930301	20	1	
MO - Ash and Coal Refuse	SI	Boron	15.49313158	19	2	
MO - Ash and Coal Refuse	SI	Cadmium	0.124406392	27	9	
MO - Ash and Coal Refuse	SI	Cobalt	4.8377	20	7	
MO - Ash and Coal Refuse	SI	Lead	0.321181411	20	11	
MO - Ash and Coal Refuse	SI	Molybdenum	0.402184211	19	15	
MO - Ash and Coal Refuse	SI	Nitrate/Nitrite	5.165	39	37	
MO - Ash and Coal Refuse	SI	Selenium	0.103823054	20	9	
O - Ash	SI	Arsenic	0.234766667	3	0	
O - Ash	SI	Boron	6.166666667	3	0	
O - Ash	SI	Molybdenum	0.0179	1	0	
O - Ash	SI	Nitrate/Nitrite	461	1	0	
O - Ash	SI	Selenium	0.0029	3	0	
OK - Ash	SI	Aluminum	40.45955556	9	0	
OK - Ash	SI	Arsenic	0.060628889	9	2	
OK - Ash	SI	Barium	0.159055556	9	1	
OK - Ash	SI	Boron	3.148333333	9	0	
OK - Ash	SI	Cadmium	0.01	9	9	
OK - Ash	SI	Lead	0.02	9	9	
OK - Ash	SI	Molybdenum	0.721694444	9	0	
OK - Ash	SI	Nitrate/Nitrite	7.62	18	17	
OK - Ash	SI	Selenium	0.282377778	9	2	
SX - Ash	SI	Aluminum	3.866609827	15	0	
SX - Ash	SI	Arsenic	0.054834273	15	2	

(continued)

CCW Constituent Data (continued)

Site/Waste Type	WMU Type	Chemical	Leachate (mg/L)	No. of Leachate Measure-ments	No. of Leachate Non-detects	Total (mg/kg)
SX - Ash	SI	Barium	0.079191593	15	0	
SX - Ash	SI	Boron	32.70433889	15	0	
SX - Ash	SI	Cadmium	0.019243353	15	5	
SX - Ash	SI	Lead	0.001228153	15	5	
SX - Ash	SI	Molybdenum	11.40518778	15	0	
SX - Ash	SI	Nitrate/Nitrite	1.6328	30	12	
SX - Ash	SI	Selenium	0.239368793	15	6	

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Appendix B. Waste Management Units

The source models supporting the coal combustion waste (CCW) risk assessment require inputs describing the characteristics of CCW waste management units (WMUs). To satisfy this requirement, the assessment used a data set of WMU area, capacity, liner type, geometry, and waste type managed for a set of individual CCW landfills and surface impoundments that are representative of the national population of coal combustion facilities that are managing their wastes onsite.

The sources for these data sets were responses to two voluntary industry surveys: an Electric Power Research Institute (EPRI) comanagement survey (for conventional utility coal combustion WMUs units) and a Council of Industrial Boiler Owners (CIBO) fluidized bed combustion (FBC) survey (for FBC WMUs). In addition to the individual WMU data, certain assumptions were required regarding (1) liner types and characteristics, (2) surface impoundment operating life, and (3) above- and below-grade geometries for WMUs. The sections below describe the two industry surveys, then discuss the data sources and assumptions made.

B.1 EPRI Comanagement Survey

For conventional utility coal combustion WMUs, the source of data for area, capacity, liner type, and waste type managed was the EPRI Coal Combustion By-Products and Low-Volume Wastes Comanagement Survey (EPRI, 1997a). In 1995, EPRI sent a 4-page questionnaire to all electric utilities with more than 100 megawatts (MW) of coal-fired generating capacity. The survey gathered data on the design of coal combustion management units and the types and volumes of waste managed. From the survey responses, EPRI prepared an electronic database and provided it to the U.S. Environmental Protection Agency (EPA) in support of the March 1999 *Report to Congress: Wastes from the Combustion of Fossil Fuels* (the RTC) (U.S. EPA, 1999a). EPRI also published a report (EPRI, 1997a) documenting the survey format and providing a brief summary of the results.

The EPRI survey responses include information on 323 waste management facilities serving 238 power plants located in 36 states. The total annual volume of CCW reported disposed by respondents to the EPRI comanagement survey is nearly 62 million tons. This quantity is two-thirds of the total generation of CCW in 1995. Therefore, the survey sample encompasses the majority of CCW disposed in terms of volume. Based on comparison with data from other sources, the EPRI survey sample appears representative of the population of coal combustion WMUs in terms of the types of units included (i.e., landfills and surface impoundments). The EPRI survey sample also is believed to be generally geographically representative of the population of conventional utility WMUs, although it may under-represent certain management practices in a few states. The EPA document, *Technical Background Document for the Supplemental Report to Congress on Remaining Fossil Fuel Combustion Wastes: Industry Statistics and Waste Management Practices* (U.S. EPA, 1999b), discusses the

representativeness of the EPRI survey in greater detail and provides extensive summary statistics on the survey responses.

The EPRI comanagement survey includes questions requesting the respondent to report the location of the WMU (by state) and the WMU area, capacity, liner type, and waste type managed. Therefore, the data set used for modeling these variables was extracted directly from the EPRI database for all active landfills and surface impoundments responding to the EPRI survey. Mine placement sites and closed WMUs were excluded from the data set. Also excluded from the data set were three responding WMUs that managed FBC waste. Data for these units were instead combined with the data set for FBC WMUs from the CIBO FBC survey (described below).

The EPRI survey data were provided in blinded form. That is, the original database did not report the identity of each respondent and identified WMU location only by state. To provide a more complete identification of the EPRI waste management locations, each unit in the EPRI database had to be matched with a specific electric utility facility. This matching was accomplished by applying professional judgment in comparing the state, waste quantity, and waste management practice information in the EPRI database with similar data from responses to the U.S. Department of Energy's Energy Information Administration (EIA) Form EIA-767 (Steam-Electric Plant Operation and Design Report) for the same year as the EPRI survey (1995). The latitude and longitude plant locations in the EIA database allowed the pairing of the EPRI WMU data with environmental setting information.

B.2 CIBO Fluidized Bed Combustion Survey

For FBC WMUs, the primary source of data for area, capacity, liner type, and waste type managed was the CIBO Fossil Fuel Fluidized Bed Combustion (FBC) Survey. In 1996, CIBO sent a voluntary questionnaire to every fossil-fuel-fired FBC plant, both utility and nonutility, in the United States. This survey collected general facility information, characterized process inputs and outputs, gathered data on waste generation and characteristics, and captured details of FBC waste management practices. From the survey responses, CIBO prepared an electronic database and provided it to EPA in support of the March 1999 RTC. CIBO also published a report (CIBO, 1997) that includes documentation of the survey format and provides a brief summary of the results.

CIBO reports a total of 84 facilities using FBC technology. Forty-five of these responded to the CIBO FBC survey, with 20 of the respondents providing information about waste management practices. The facilities with waste management data cover 24 percent of all U.S. facilities using FBC. The CIBO sample is geographically representative of the full population, with the exception of two states that appear under-represented in the sample—Pennsylvania and Illinois. EPA's technical background document on industry statistics and waste management practices (U.S. EPA, 1999b) discusses the representativeness of the EPRI survey in greater detail and provides extensive summary statistics on the survey responses.

The CIBO survey includes questions requesting the respondent to report WMU area, capacity, liner type, and waste type managed. Therefore, the data set used for modeling these variables was extracted directly from the CIBO database. The CIBO respondents include both

utility and nonutility (i.e., industrial or institutional facilities that burn coal, but are not primarily engaged in the business of selling electricity) facilities. Because nonutilities are outside the scope of this risk assessment, nonutilities were excluded from the data set. Three additional utility facilities were excluded from the data set because their responses contained insufficient data on the variables of interest (area, capacity, liner type, and waste type). Mine placement sites also were excluded from the data set. Data for the FBC units responding to the EPRI survey (see above) were added to the data set. This resulted in a sample of seven FBC landfills and one FBC surface impoundment for modeling. Table B-1 compares this sample to the waste management practices of the full utility FBC population.

As shown in Table B-1, FBC facilities frequently avoid waste disposal units by directing all of their waste to mine placement or beneficial use. Therefore, although only 8 of the 41 utility FBC facilities are included in the model data set, these 8 facilities represent nearly all of the known FBC landfills and surface impoundments.

Table B-1. Utility FBC Waste Management Practices and Units Modeled

Number of Facilities...	Total	Landfill	Surface Impoundment	Minefill or Beneficial Use	Unknown
in the full population	41	11	1	16	13
modeled	8	7	1	Not applicable	Not applicable

The CIBO survey database identified the location of each WMU in detail (latitude and longitude). Therefore, no additional analysis was necessary to pair the WMU data with environmental setting information.

B.3 Liner Type

The EPRI survey data included information on the liner (if any) for each WMU. For this assessment, the WMUs were assigned to one of three liner scenarios based on the EPRI liner data: an unlined (no liner) scenario, a compacted clay liner, and a composite liner that combines a plastic (e.g., high-density polyethylene (HDPE) membrane) over either geosynthetic or natural clays. These three scenarios correspond to the following conceptual liner scenarios, developed in support of EPA's Industrial Subtitle D guidance (U.S. EPA, 2002), which can be selected in the landfill and surface impoundment models used in this assessment.

- **Unlined Scenario.** For landfills, waste is placed directly on local soils, either on grade or excavated to some design depth and without a leachate collection system. After the landfill has been filled to capacity, a 2-foot native soil cover (the minimum required by Subtitle D regulations) is installed and assumed to support vegetation. For surface impoundments, wastewater is placed directly on local soils, and the depth of water is constant over the entire life of the impoundment, pre- and post-closure. Sediments accumulate and consolidate at the bottom of the impoundment and migrate into the underlying native soils, where they clog pore spaces and provide some barrier to flow.

- **Clay Liner Scenario.** For landfills, waste is placed directly on a 3-foot compacted clay liner, which is installed on the local soils, either on grade or excavated to some design depth and without a leachate collection system. After the landfill has been filled to capacity, a 3-foot clay cover is installed and covered with 1 foot of loam to support vegetation and drainage. The hydraulic conductivity of both the liner and cover clays is assumed to be $1x10^{-7}$ cm/sec. For surface impoundments, wastewater is placed on a compacted clay liner, which is installed on the local soils. The assumptions for an unlined impoundment also apply to the compacted clay liner scenario, except that a compacted clay liner filters out the sediments that clog the native soils in the unlined case, so the effect of clogging the native materials is not included in the calculation of the infiltration rate. The thickness of the compacted clay liner was assumed to be 3 feet and the hydraulic conductivity was assumed to be $1x10^{-7}$ cm/sec.

- **Composite Liner Scenario.** For landfills, wastes are placed on a liner system that consists of a 60 mil HDPE membrane with either an underlying geosynthetic clay liner with a maximum hydraulic conductivity of $5x10^{-9}$ cm/sec, or a 3-foot compacted clay liner with a maximum hydraulic conductivity of $1x10^{-7}$ cm/sec. A leachate collection system is also assumed to exist between the waste and the liner system. After the landfill has been filled to capacity, a 3-foot clay cover is assumed to be installed and covered with 1 foot of loam to support vegetation and drainage. For surface impoundments, wastewater is placed on a synthetic membrane with an underlying geosynthetic or natural compacted clay liner with a hydraulic conductivity of $1x10^{-7}$ cm/sec. The membrane liner was assumed to have a number of pinhole leaks of uniform size (6 mm^2). The number of these leaks was based on an empirical distribution of membrane leak density values obtained from TetraTech (2001), as described in the *IWEM Technical Background Document* (U.S. EPA, 2002).

Table B-2 shows the crosswalk used to assign one of the three liner scenarios to each facility based on the liner data in the EPRI survey data (EPRI, 1997a). Attachment B-2 provides these assignments, along with the original EPRI liner type, for each CCW landfill facility modeled.

Table B-2. Crosswalk Between EPRI and CCW Source Model Liner Types

EPRI Liner Type	Model Liner Code	Description
Compacted ash	0	no liner
Compacted clay	1	clay
Composite clay/membrane	2	composite
Double	2	composite
Geosynthetic membrane	2	composite
None/natural soils	0	no liner

B.4 Surface Impoundment Operating Life

The model runs for surface impoundments required a general assumption about the length of the operating life for these WMUs. Of the surface impoundments in the EPRI comanagement survey, 86 provided responses to questions about both the unit's opening date and expected closure date. From these two dates, an expected operating life for each impoundment can be calculated. An additional 30 impoundments provided an opening date, but no closure date. One possible interpretation of these responses is that these facilities do not expect to close in the foreseeable future, corresponding to a very long or indefinite operating life with dredging of waste to maintain capacity. Figure B-1 shows the distribution of the calculated operating lives, along with a bar showing the facilities with no closure date.

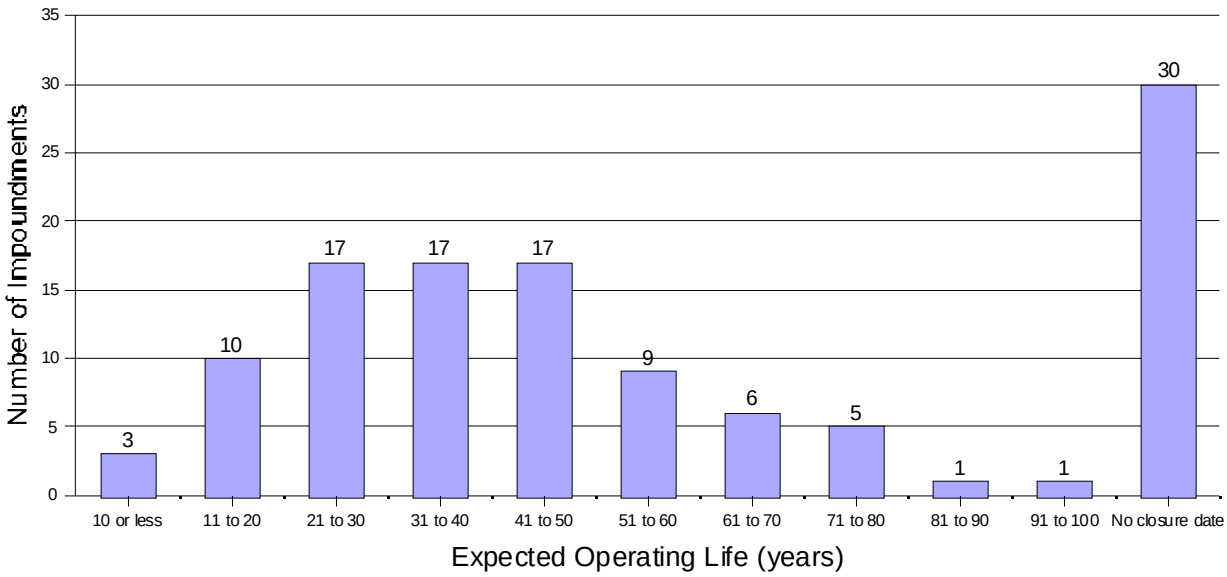

Figure B-1. Operating life of impoundments in the EPRI survey.

Based on these data, a 75-year operating life was chosen. This value corresponds to the 95th percentile of the observed distribution. While the use of a 95th percentile value may appear conservative, if many of the facilities with no closure date do, in fact, plan to operate indefinitely, 75 years would correspond to a much lower percentile in the distribution. More significantly, many CCW surface impoundments close with wastes in place. The selection of 75 years minimizes the underestimation of chronic risks for this scenario, given that EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) surface impoundment model assumes clean closure after the operating life.

B.5 Above- and Below-Grade Geometry

The model runs for surface impoundments and landfills required general assumptions about the geometry of these units with respect to the ground surface (i.e., how much of the unit's depth is below grade). The CIBO FBC survey included data on this geometry, so, for FBC units, these data were extracted directly from the database along with the other individual WMU data

(e.g., capacity). The EPRI comanagement survey did not contain data describing above- and below-grade geometry. Therefore, for conventional utility coal combustion WMUs, EPA reviewed 17 site-characterization reports published by EPRI (EPRI 1991; 1992; 1994a,b; 1996a,b; 1997b-k) and determined an above- versus below-grade geometry for each unit described in those reports based on schematic diagrams and site descriptions. EPA also extracted data from another CIBO voluntary survey that covered conventional (non-FBC) nonutility coal combustors. Figures B-2 and B-3 display the distributions of the data thus collected.

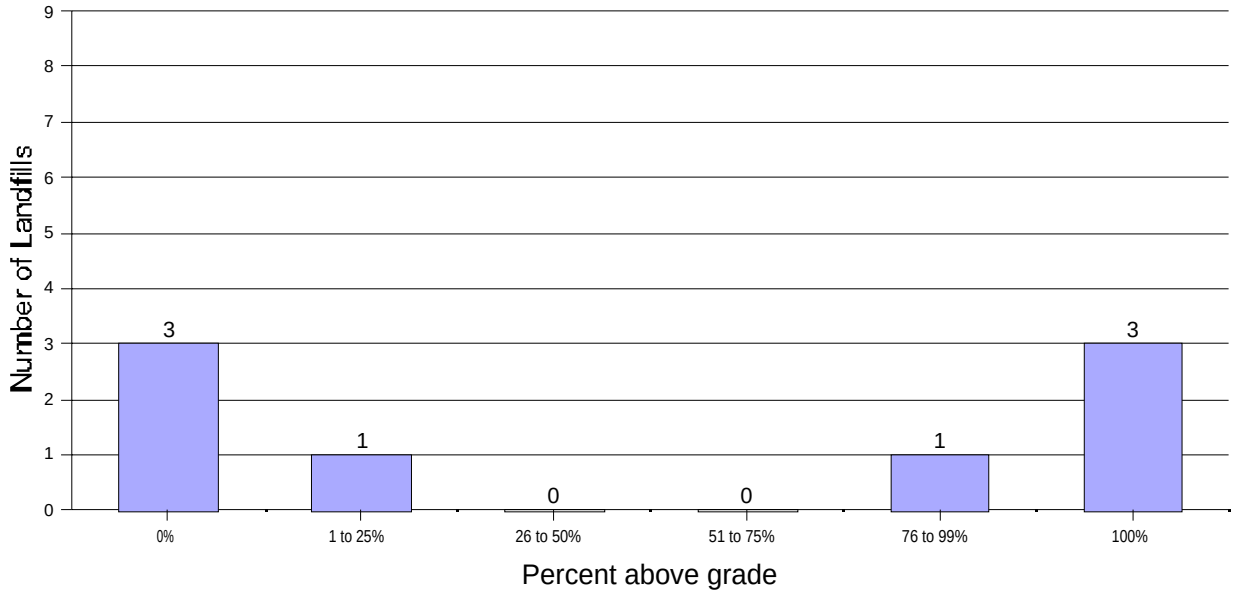

Figure B-2. Above- and below-grade geometry for landfills.

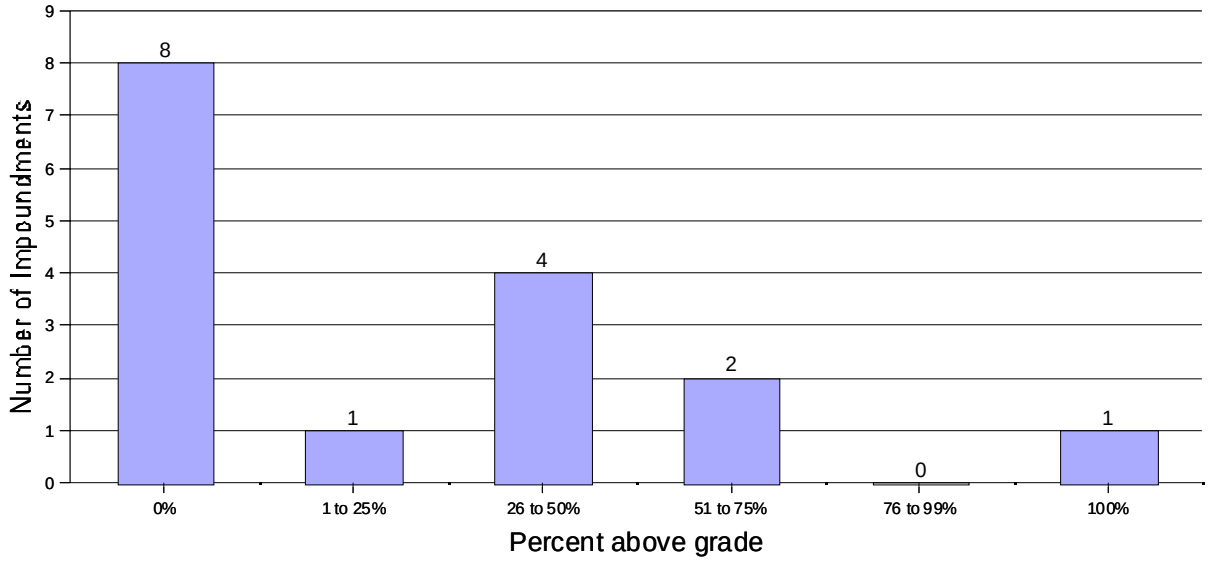

Figure B-3. Above- and below-grade geometry for impoundments.

For landfills, because the data were limited (8 sites), the model runs assume that the percent below grade ranges from 1 to 100 and is uniformly distributed. For each landfill iteration, a random value for percent below grade is picked and applied to the landfill depth to determine depth below ground surface. This value is constrained to be no deeper than the water table and is checked to see that EPACMTP groundwater mounding constraints are not violated.

For surface impoundments, more data were available (16 sites), with 8 sites being constructed entirely below grade and the remaining 8 sites ranging from 7.5 to 45 feet above grade. For each surface impoundment iteration, height above grade at these 15 sites is randomly sampled as an empirical distribution and applied to the overall surface impoundment depth to determine depth below ground surface.

B.6 Calculation of WMU Depth and Imputation of Missing WMU Data

The EPRI survey includes information on the total area and total waste capacity of each landfill and surface impoundment included in the survey. To calculate average depth for each WMU (a necessary EPACMTP model input), the total waste capacity was divided by the area. The resulting depths were then checked for reasonableness. For surface impoundments, one depth (1 foot) was culled as being unrealistically low and one (700 feet) as too high. Two landfill depths less than 2 feet and one depth greater than 350 feet were also removed from the database. In these cases the EPRI waste capacity data were culled and replaced using the regressions described below (i.e., WMU areas are considered more reliable than the capacity estimates in the survey data), and new capacities were estimated as described below.

In addition, four landfills and six surface impoundments had neither area nor capacity data in the EPRI survey. In these cases, the EIA facility locations were used to find the plants and their WMUs on aerial photos from the Terraserver Web site (http://terraserver-usa.com/geographic.aspx), and a geographic information system (GIS) was used to measure the areas of the units in question. Capacities were then estimated as described below.

To impute data for facilities missing either area or capacity data in the EPRI survey, linear regression equations were developed based on WMUs with both area and capacity data, one to predict area from capacity, and one to predict capacity from area. The final regression equations are shown in Figures B-4 and B-5 for landfills and Figures B-6 and B-7 for surface impoundments. In each case, a standard deviation around the regression line was also computed and used during source data file preparation to randomly vary the area or capacity from iteration to iteration within the bounds of the existing data set.

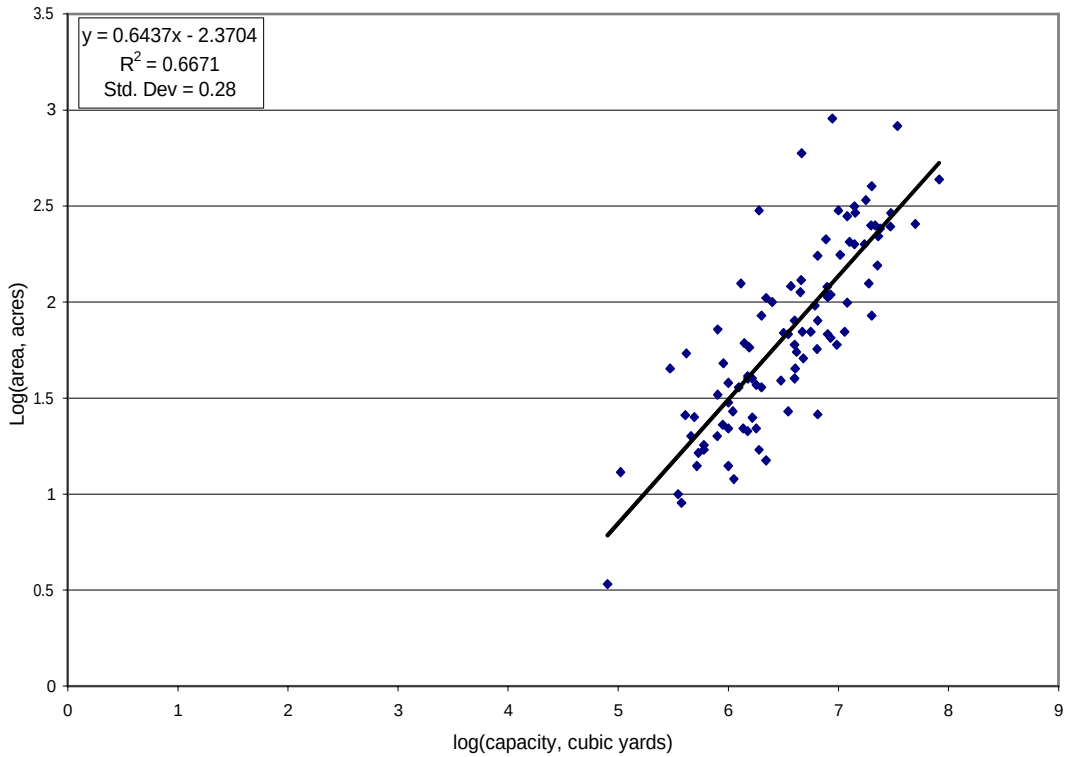

Figure B-4. Linear regression to impute landfill area from capacity.

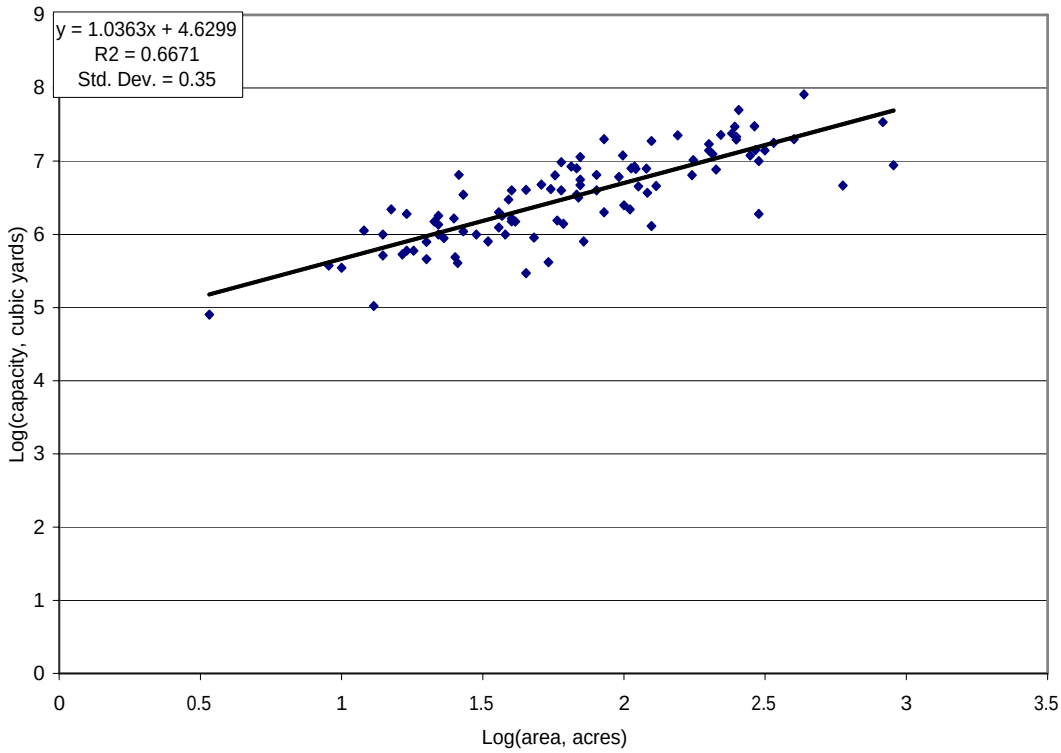

Figure B-5. Linear regression to impute landfill capacity from area.

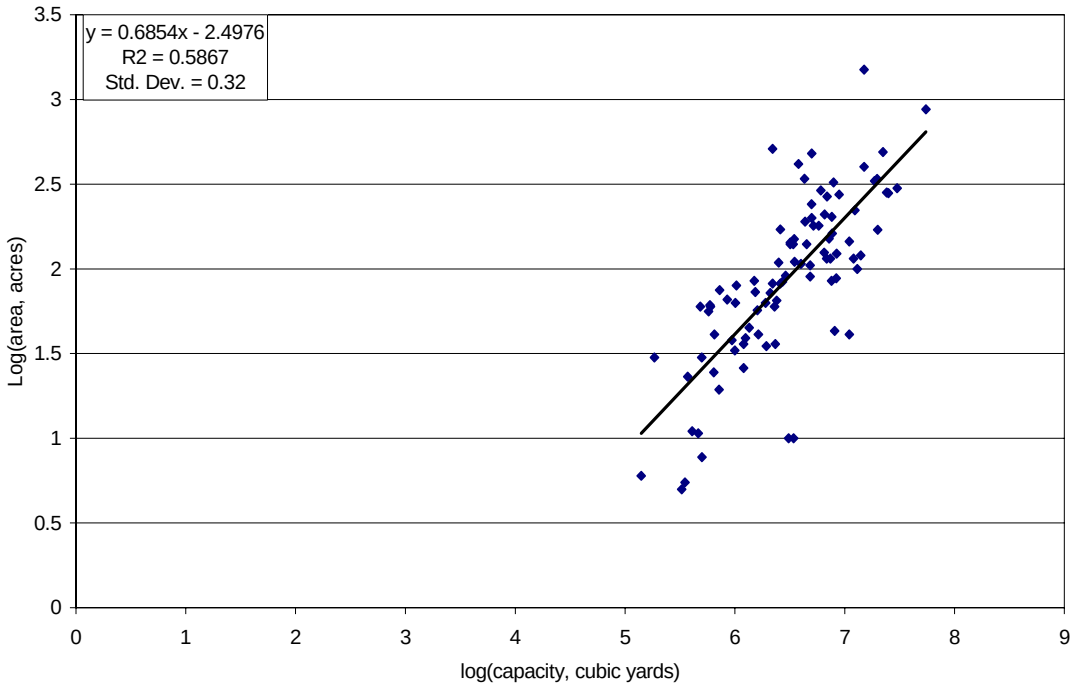

Figure B-6. Linear regression to impute surface impoundment area from capacity.

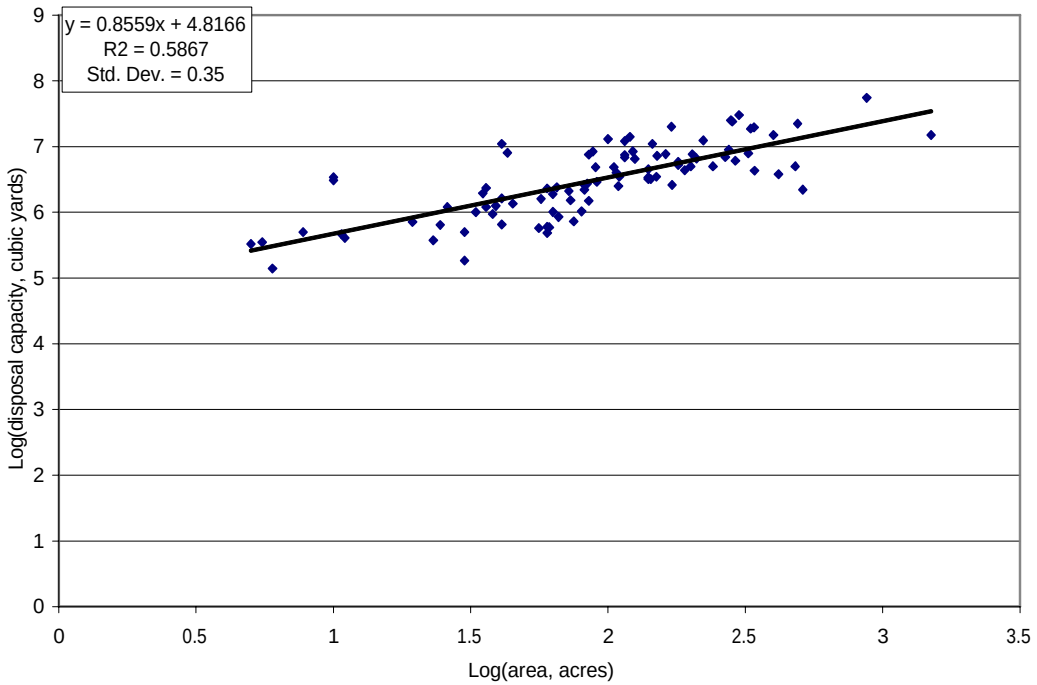

Figure B-7. Linear regression to impute surface impoundment capacity from area.

B.7 Results

Attachment B-1 lists the 181 CCW disposal sites modeled in this risk assessment and their locations. The WMU data used in the CCW risk assessment for each of the 108 landfills and 96 surface impoundments at these coal combustion facilities are presented in Attachment B-2. Missing data that were randomly replaced as described above are not represented in the table (i.e., the fields are left blank).

B.8 References

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Attachment B-1: CCW Disposal Sites (Plants)

Plant Name	Utility Name	County	State	Latitude	Longitude
A B Brown	Southern Indiana Gas & Elec. Co.	Posey	IN	37.9053	87.715
A/C Power - Ace Operations	A.C.E. Cogeneration Co.	San Bernardino	CA	35.75	117.3667
Allen	Tennessee Valley Authority	Shelby	TN	35.0742	90.1492
Alma	Dairyland Power Coop	Buffalo	WI	44.3078	91.905
Antelope Valley	Basin Electric Power Coop	Mercer	ND	47.37	101.8353
Arkwright	Georgia Power Co.	Bibb	GA	32.9269	83.6997
Asheville	Carolina Power & Light Co.	Buncombe	NC	35.4714	82.5431
Baldwin	Illinois Power Co.	Randolph	IL	38.205	89.8544
Barry	Alabama Power Co.	Mobile	AL	31.0069	88.0103
Bay Front	Northern States Power Co.	Ashland	WI	43.4833	89.4
Bay Shore	Toledo Edison Co.	Lucas	OH	41.6925	83.4375
Belews Creek	Duke Power Co.	Stokes	NC	36.2811	80.0603
Ben French	Black Hills Corp.	Pennington	SD	44.0872	103.2614
Big Cajun 2	Cajun Electric Power Coop, Inc.	Pointe Coupee	LA	30.7283	91.3686
Big Sandy	Kentucky Power Co.	Lawrence	KY	38.1686	82.6208
Big Stone	Otter Tail Power Co.	Grant	SD	45.3047	96.5083
Black Dog Steam Plant	Northern States Power Company	Dakota	MN	44.8167	93.25
Blue Valley	Independence, City of	Jackson	MO	39.0919	94.3364
Bowen	Georgia Power Co.	Bartow	GA	34.1256	84.9192
Brandon Shores	Baltimore Gas & Electric Co.	Anne Arundel	MD	39.18	76.5333
Buck	Duke Power Co.	Rowan	NC	35.7133	80.3767
Bull Run	Tennessee Valley Authority	Anderson	TN	36.0211	84.1567
C D McIntosh Jr.	Lakeland, City of	Polk	FL	28.075	81.9292
C P Crane	Baltimore Gas & Electric Co.	Baltimore City	MD	39.2845	76.6207
Cape Fear	Carolina Power & Light Co.	Chatham	NC	35.5989	79.0492
Carbon	PacifiCorp	Carbon	UT	39.7264	110.8639
Cardinal	Cardinal Operating Co.	Jefferson	OH	40.2522	80.6486
Cayuga	PSI Energy, Inc.	Vermillion	IN	39.9008	87.4136
Chalk Point	Potomac Electric Power Co.	Prince Georges	MD	38.5639	76.6806
Cholla	Arizona Public Service Co.	Navajo	AZ	34.9414	110.3003
Cliffside	Duke Power Co.	Cleveland	NC	35.22	81.7594
Clover	Virginia Electric & Power Co.	Halifax	VA	36.8667	78.7
Coal Creek	Coop Power Assn.	McLean	ND	47.3789	101.1572
Coleto Creek	Central Power & Light Co.	Goliad	TX	28.7128	97.2142

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Colstrip	Montana Power Co.	Rosebud	MT	45.8844	106.6139
Conemaugh	GPU Service Corporation	Indiana	PA	40.3842	79.0611
Conesville	Columbus Southern Power Co.	Coshocton	OH	40.1842	81.8811
Council Bluffs	MidAmerican Energy Co.	Pottawattamie	IA	41.18	95.8408
Crawford	Commonwealth Edison Co.	Cook	IL	39.8225	90.5681
Crist	Gulf Power Co.	Escambia	FL	30.5658	87.2239
Cross	South Carolina Pub Serv. Auth.	Berkeley	SC	33.3694	80.1119
Cumberland	Tennessee Valley Authority	Stewart	TN	36.3942	87.6539
Dale	East Kentucky Power Coop, Inc.	Clark	KY	37.875	84.25
Dallman	Springfield, City of	Sangamon	IL	39.7547	89.6008
Dan E Karn	Consumers Energy Co.	Bay	MI	43.645	83.8414
Dan River	Duke Power Co.	Rockingham	NC	36.4861	79.7244
Danskammer	Central Hudson Gas & Elec. Corp.	Orange	NY	41.5719	73.9664
Dave Johnston	PacifiCorp	Converse	WY	42.8333	105.7667
Dickerson	Potomac Electric Power Co.	Montgomery	MD	39.144	77.2059
Dolet Hills	CLECO Corporation	De Soto	LA	32.0308	93.5644
Duck Creek	Central Illinois Light Co.	Fulton	IL	40.4644	89.9825
Dunkirk	Niagara Mohawk Power Corp.	Chautauqua	NY	42.4919	79.3469
E D Edwards	Central Illinois Light Co.	Peoria	IL	40.5961	89.6633
E W Brown	Kentucky Utilities Co.	Mercer	KY	37.7911	84.7147
Eckert Station	Lansing, City of	Ingham	MI	42.7189	84.5583
Edgewater	Wisconsin Power & Light Co.	Sheboygan	WI	43.7181	87.7092
Elmer W Stout	Indianapolis Power & Light Co.	Marion	IN	39.7122	86.1975
F B Culley	Southern Indiana Gas & Elec. Co.	Warrick	IN	37.91	87.3267
Fayette Power Prj.	Lower Colorado River Authority	Fayette	TX	29.9172	96.7506
Flint Creek	Southwestern Electric Power Co.	Benton	AR	36.2625	94.5208
Fort Martin	Monongahela Power Co.	Monongalia	WV	39.7	79.9167
Frank E Ratts	Hoosier Energy R E C, Inc.	Pike	IN	38.5186	87.2725
G G Allen	Duke Power Co.	Gaston	NC	35.1897	81.0122
Gadsden	Alabama Power Co.	Etowah	AL	34.0136	85.9703
Gallatin	Tennessee Valley Authority	Sumner	TN	36.3156	86.4006
Gen J M Gavin	Ohio Power Co.	Gallia	OH	38.9358	82.1164
Genoa	Dairyland Power Coop	Vernon	WI	43.5592	91.2333
Gibson	PSI Energy, Inc.	Gibson	IN	38.3589	87.7783
Gorgas	Alabama Power Co.	Walker	AL	33.5111	87.235
Green River	Kentucky Utilities Co.	Muhlenberg	KY	37.3636	87.1214
Greene County	Alabama Power Co.	Greene	AL	32.6	87.7667
H B Robinson	Carolina Power & Light Co.	Darlington	SC	34.4	80.1667
Hammond	Georgia Power Co.	Floyd	GA	34.3333	85.2336

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Harllee Branch	Georgia Power Co.	Putnam	GA	33.1942	83.2994
Harrison	Monongahela Power Co.	Harrison	WV	39.3833	80.3167
Hatfield's Ferry	West Penn Power Co.	Greene	PA	39.85	79.9167
Hennepin	Illinois Power Co.	Putnam	IL	41.3028	89.315
Heskett	Montana-Dakota Utilities Co.	Morton	ND	46.8669	100.8839
Holcomb	Sunflower Electric Power Corp.	Finney	KS	37.9319	100.9719
Homer City	GPU Service Corporation	Indiana	PA	40.5142	79.1969
Hoot Lake	Otter Tail Power Co.	Otter Tail	MN	46.29	96.0428
Hugo	Western Farmers Elec. Coop, Inc.	Choctaw	OK	34.0292	95.3167
Hunter	PacifiCorp	Emery	UT	39.1667	111.0261
Huntington	PacifiCorp	Emery	UT	39.3792	111.075
Intermountain	Los Angeles, City of	Millard	UT	39.5108	112.5792
J H Campbell	Consumers Energy Co.	Ottawa	MI	42.9103	86.2031
J M Stuart	Dayton Power & Light Co.	Adams	OH	38.6364	83.7422
J R Whiting	Consumers Energy Co.	Monroe	MI	41.7914	83.4486
Jack McDonough	Georgia Power Co.	Cobb	GA	33.8244	84.475
Jack Watson	Mississippi Power Co.	Harrison	MS	30.4392	89.0264
James H Miller Jr.	Alabama Power Co.	Jefferson	AL	33.6319	87.0597
Jim Bridger	PacifiCorp	Sweetwater	WY	41.75	108.8
John E Amos	Appalachian Power Co.	Putnam	WV	38.4731	81.8233
John Sevier	Tennessee Valley Authority	Hawkins	TN	36.3767	82.9639
Johnsonville	Tennessee Valley Authority	Humphreys	TN	36.0278	87.9861
Joliet 29	Commonwealth Edison Co.	Will	IL	41.4892	88.0844
Keystone	GPU Service Corporation	Armstrong	PA	40.6522	79.3425
Killen Station	Dayton Power & Light Co.	Adams	OH	38.6903	83.4803
Kingston	Tennessee Valley Authority	Roane	TN	35.8992	84.5194
Kraft	Savannah Electric & Power Co	Chatham	GA	32.1333	81.1333
L V Sutton	Carolina Power & Light Co.	New Hanover	NC	34.2831	77.9867
Lansing	Interstate Power Co.	Allamakee	IA	43.3386	91.1667
Laramie R Station	Basin Electric Power Coop	Platte	WY	42.1086	104.8711
Lawrence EC	KPL Western Resources Co.	Douglas	KS	39.0078	95.2681
Lee	Carolina Power & Light Co.	Wayne	NC	35.3778	78.1
Leland Olds	Basin Electric Power Coop	Mercer	ND	47.2833	101.4
Lon Wright	Fremont, City of	Dodge	NE	41.45	96.5167
Louisa	MidAmerican Energy Co.	Louisa	IA	41.3181	91.0931
Marion	Southern Illinois Power Coop	Williamson	IL	37.6167	88.95
Marshall	Duke Power Co.	Catawba	NC	35.5975	80.9658
Martin Lake	Texas Utilities Electric Co.	Rusk	TX	32.2606	94.5708
Mayo	Carolina Power & Light Co.	Person	NC	36.5278	78.8919
Meramec	Union Electric Co.	St Louis	MO	38.6522	90.2397

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Merom	Hoosier Energy R E C, Inc.	Sullivan	IN	39.0694	87.5108
Miami Fort	Cincinnati Gas & Electric Co.	Hamilton	OH	39.1111	84.8042
Milton R Young	Minnkota Power Coop, Inc.	Oliver	ND	47.0664	101.2139
Mitchell - PA	West Penn Power Co.	Washington	PA	40.2167	79.9667
Mitchell - WV	Ohio Power Co.	Marshall	WV	39.8297	80.8153
Mohave	Southern California Edison Co.	Clark	NV	35.1667	114.6
Monroe	Detroit Edison Co.	Monroe	MI	41.8911	83.3444
Morgantown	Potomac Electric Power Co.	Charles	MD	38.3611	76.9861
Mountaineer (1301)	Appalachian Power Co.	Mason	WV	38.9794	81.9344
Mt Storm	Virginia Electric & Power Co.	Grant	WV	39.2014	79.2667
Muscatine Plant #1	Muscatine, City of	Muscatine	IA	41.3917	91.0569
Muskogee	Oklahoma Gas & Electric Co.	Muskogee	OK	35.7653	95.2883
Neal North	MidAmerican Energy Co.	Woodbury	IA	42.3167	96.3667
Neal South	MidAmerican Energy Co.	Woodbury	IA	42.3022	96.3622
Nebraska City	Omaha Public Power District	Otoe	NE	40.625	95.7917
New Castle	Pennsylvania Power Co.	Lawrence	PA	40.9383	80.3683
Newton	Central Illinois Pub Serv. Co.	Jasper	IL	38.9364	88.2778
North Omaha	Omaha Public Power District	Douglas	NE	41.33	95.9467
Northeastern	Public Service Co. of Oklahoma	Rogers	OK	36.4222	95.7047
Nucla	Tri-State G & T Assn., Inc.	Montrose	CO	38.2386	108.5072
Oklaunion	West Texas Utilities Co.	Wilbarger	TX	34.0825	99.1753
Paradise	Tennessee Valley Authority	Muhlenberg	KY	37.2608	86.9783
Petersburg	Indianapolis Power & Light Co.	Pike	IN	38.5267	87.2522
Pleasant Prairie	Wisconsin Electric Power Co.	Kenosha	WI	42.5381	87.9033
Port Washington	Wisconsin Electric Power Co.	Ozaukee	WI	43.3908	87.8686
Portland	Metropolitan Edison Co.	Northampton	PA	40.7525	75.3324
Possum Point	Virginia Electric & Power Co.	Prince William	VA	38.5367	77.2806
Potomac River	Potomac Electric Power Co.	Alexandria	VA	38.8078	77.0372
Presque Isle	Wisconsin Electric Power Co.	Marquette	MI	46.5694	87.3933
R Gallagher	PSI Energy, Inc.	Floyd	IN	38.2631	85.8378
R M Schahfer	Northern Indiana Pub. Serv. Co.	Jasper	IN	41.2167	87.0222
Reid Gardner	Nevada Power Co.	Clark	NV	36.6606	114.625
Richard Gorsuch	American Mun. Power-Ohio, Inc.	Washington	OH	39.3672	81.5208
Riverbend	Duke Power Co.	Gaston	NC	35.36	80.9742
Rodemacher	CLECO Corporation	Rapides	LA	31.395	92.7167
Roxboro	Carolina Power & Light Co.	Person	NC	36.4831	79.0711
Sandow	Texas Utilities Electric Co.	Milam	TX	30.5642	97.0639
Scherer	Georgia Power Co.	Monroe	GA	33.0583	83.8072
Shawnee	Tennessee Valley Authority	McCracken	KY	37.1517	88.775
Shawville	GPU Service Corporation	Clearfield	PA	41.0681	78.3661

(continued)

CCW Disposal Sites (Plants) (continued)

Plant Name	Utility Name	County	State	Latitude	Longitude
Sheldon	Nebraska Public Power District	Lancaster	NE	40.5589	96.7842
South Oak Creek	Wisconsin Electric Power Co.	Milwaukee	WI	42.8014	87.8314
Springerville	Tucson Electric Power Co	Apache	AZ	34.3186	109.1636
St Johns River Power	JEA	Duval	FL	30.4308	81.5508
Stanton Energy Ctr.	Orlando Utilities Comm.	Orange	FL	28.4822	81.1678
Stockton Cogen Company	Stockton Cogen Co (operator: Air Products)	San Joaquin	CA	37.9778	121.2667
Syl Laskin	Minnesota Power, Inc.	St Louis	MN	47.53	92.1617
Tecumseh EC	KPL Western Resources Co.	Shawnee	KS	39.0528	95.5683
Texas-New Mexico	Texas-New Mexico Power Company/Sempra Energy	Robertson	TX	31.0928	96.6933
Titus	Metropolitan Edison Co.	Berks	PA	40.3047	75.9072
Trimble County	Louisville Gas & Electric Co.	Trimble	KY	38.5678	85.4139
Tyrone	Kentucky Utilities Co.	Woodford	KY	38.0213	84.7456
Valley	Wisconsin Electric Power Co.	Milwaukee	WI	43.0303	87.925
Vermilion	Illinois Power Co.	Vermilion	IL	40.1781	87.7481
Victor J Daniel Jr.	Mississippi Power Co.	Jackson	MS	30.5322	88.5569
W A Parish	Houston Lighting & Power Co.	Fort Bend	TX	29.4833	95.6331
W H Weatherspoon	Carolina Power & Light Co.	Robeson	NC	34.5889	78.975
W S Lee	Duke Power Co.	Anderson	SC	34.6022	82.435
Wabash River	PSI Energy, Inc.	Vigo	IN	39.5278	87.4222
Walter C Beckjord	Cincinnati Gas & Electric Co.	Clermont	OH	38.9917	84.2972
Wansley	Georgia Power Co.	Heard	GA	33.4167	85.0333
Warrick	Southern Indiana Gas & Elec. Co.	Warrick	IN	37.915	87.3319
Waukegan	Commonwealth Edison Co.	Lake	IL	42.3833	87.8083
Weston	Wisconsin Public Service Corp.	Marathon	WI	44.8617	89.655
Widows Creek	Tennessee Valley Authority	Jackson	AL	34.8825	85.7547
Will County	Commonwealth Edison Co.	Will	IL	38.8639	90.1347
Wyodak	PacifiCorp	Campbell	WY	44.2833	105.4
Yates	Georgia Power Co.	Coweta	GA	33.4631	84.955

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Attachment B-2: CCW WMU Data

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
A B Brown	42	LF	176	10360000	Ash	compacted clay	clay
A/C Power - Ace Operations	3000	LF	18	1030815	FBC	none/natural soils	no liner
Allen	293	SI	85	1500000	Ash	none/natural soils	no liner
Alma	7	LF	85	2000000	Ash and Coal Waste	composite clay/membrane	composite
Antelope Valley	57	LF	27	3500000	Ash	none/natural soils	no liner
Arkwright	198	LF	54	415907	Ash and Coal Waste	none/natural soils	no liner
Asheville	159	SI	140	3200000	Ash	none/natural soils	no liner
Baldwin	2	SI	107	4000000	Ash and Coal Waste	none/natural soils	no liner
Barry	301	SI	63	1900000	Ash and Coal Waste	none/natural soils	no liner
Bay Front	81	LF	10	350000	Ash	none/natural soils	no liner
Bay Shore	32	LF	85		Ash	none/natural soils	no liner
Belews Creek	167	SI	512	2200000	Ash and Coal Waste	none/natural soils	no liner
Belews Creek	168	LF	315	14000000	Ash	compacted ash	no liner
Ben French	14	LF	4.61		Ash	compacted clay	clay
Big Cajun 2	186	SI	241	4990003	Ash	compacted clay	clay
Big Sandy	138	SI	115	12052100	Ash and Coal Waste	none/natural soils	no liner
Big Stone	15	LF	3.4	80000	Ash	compacted clay	clay
Big Stone	41	LF	106	8000000	Ash	none/natural soils	no liner
Black Dog Steam Plant	2700	LF	96	8936296	FBC	compacted clay	clay
Blue Valley	176	SI	23.1	372000	Ash and Coal Waste	compacted clay	clay
Bowen	143	LF	25.24	491400	Ash	compacted ash	no liner
Bowen	144	LF	25.77	406971	Ash	compacted ash	no liner
Brandon Shores	339	LF	246	5600000	Ash and Coal Waste	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Buck	235	SI	90	4840000	Ash and Coal Waste	none/natural soils	no liner
Bull Run	296	SI	41	650000	Ash and Coal Waste	none/natural soils	no liner
C D McIntosh Jr.	223	LF	26		Ash and Coal Waste	compacted ash	no liner
C P Crane	338	LF	35	800000	Ash	none/natural soils	no liner
Cape Fear	161	SI	60	2300000	Ash	none/natural soils	no liner
Carbon	263	lf	11.7739066		Ash and Coal Waste	none/natural soils	no liner
Cardinal	126	SI	123	8437500	Ash	none/natural soils	no liner
Cayuga	325	SI	280	25000000	Ash and Coal Waste	none/natural soils	no liner
Chalk Point	292	LF	596	4634000	Ash and Coal Waste	none/natural soils	no liner
Cholla	107	SI	171	2600000	Ash	none/natural soils	no liner
Cliffside	163	SI	82	2200000	Ash	compacted clay	clay
Clover	139	LF	22	1000000	Ash	geosynthetic membrane	composite
Coal Creek	29	LF	70	4700000	Ash	compacted clay	clay
Coal Creek	30	LF	220	23000000	Ash	composite clay/membrane	composite
Coleto Creek	190	si	314.6135409		Ash and Coal Waste	compacted clay	clay
Colstrip	89	LF	9		Ash	none/natural soils	no liner
Conemaugh	101	LF	434	82000000	Ash	geosynthetic membrane	composite
Conesville	250	LF	300	10000000	Ash	compacted clay	clay
Conesville	251	LF	100	2500000	Ash and Coal Waste	none/natural soils	no liner
Council Bluffs	94	SI	200		Ash	none/natural soils	no liner
Crawford	272	SI	24.5	642000	Ash and Coal Waste	compacted clay	clay
Crist	157	LF	12		Ash and Coal Waste	none/natural soils	no liner
Cross	264	LF	320		Ash	compacted ash	no liner
Cross	265	LF	30		Ash and Coal Waste	none/natural soils	no liner
Cross	266	LF	30		Ash and Coal Waste	none/natural soils	no liner
Cross	267	LF	230		Ash and Coal Waste	none/natural soils	no liner
Cross	268	LF	60		Ash and Coal Waste	compacted clay	clay

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Cumberland	294	SI	75	1750000	Ash and Coal Waste	none/natural soils	no liner
Cumberland	303	SI	295	9500000	Ash	none/natural soils	no liner
Dale	151	SI	115	7408274	Ash and Coal Waste	none/natural soils	no liner
Dallman	178	LF	22	1800000	Ash	compacted clay	clay
Dallman	179	SI	417	3800000	Ash	none/natural soils	no liner
Dan E Karn	6	LF	40	1650000	Ash and Coal Waste	geosynthetic membrane	composite
Dan River	234	SI	72	2097000	Ash and Coal Waste	none/natural soils	no liner
Danskammer	24	LF	14	517265	Ash and Coal Waste	geosynthetic membrane	composite
Dave Johnston	13	LF	45	296100	Ash	compacted clay	clay
Dickerson	290	LF	206	12600000	Ash	none/natural soils	no liner
Dolet Hills	245	SI	66	850000	Ash and Coal Waste	none/natural soils	no liner
Dolet Hills	246	LF	109	8500000	Ash	compacted clay	clay
Duck Creek	11	LF	21.3	1500000	Ash	compacted clay	clay
Dunkirk	49	LF	12	1126080	Ash	compacted clay	clay
E D Edwards	276	SI	145	11000000	Ash and Coal Waste	none/natural soils	no liner
E W Brown	313	SI	33	1000000	Ash	none/natural soils	no liner
E W Brown	314	SI	84	2710000	Ash	none/natural soils	no liner
Eckert Station	113	LF	174	6460000	Ash	none/natural soils	no liner
Eckert Station	114	SI	151	7200000	Ash	none/natural soils	no liner
Edgewater	289	LF	25	1655700	Ash and Coal Waste	none/natural soils	no liner
Elmer W Stout	130	SI	10	3420000	Ash	geosynthetic membrane	composite
F B Culley	183	SI	82	2600000	Ash and Coal Waste	none/natural soils	no liner
Fayette Power Prj.	195	SI	190	4351644	Ash	compacted clay	clay
Fayette Power Prj.	196	LF	23	890560	Ash	geosynthetic membrane	composite
Flint Creek	191	LF	40	1508250	Ash and Coal Waste	none/natural soils	no liner
Flint Creek	192	si	35.73857178		Ash and Coal Waste	none/natural soils	no liner
Fort Martin	213	LF	17	1900000	Ash	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Fort Martin	214	LF	61	1400000	Ash	double	composite
Fort Martin	215	LF	121	3700000	Ash and Coal Waste	composite clay/membrane	composite
Frank E Ratts	182	SI	39	1250000	Ash and Coal Waste	none/natural soils	no liner
G G Allen	237	SI	210	6545000	Ash and Coal Waste	none/natural soils	no liner
Gadsden	283	SI	60	484000	Ash and Coal Waste	compacted clay	clay
Gallatin	304	SI	341	4300000	Ash and Coal Waste	none/natural soils	no liner
Gen J M Gavin	135	LF	255	50000000	Ash	composite clay/membrane	composite
Gen J M Gavin	136	SI	300	30000000	Ash and Coal Waste	none/natural soils	no liner
Gen J M Gavin	137	LF	99	12000000	Ash	compacted clay	clay
Genoa	244	LF	100		Ash and Coal Waste	none/natural soils	no liner
Gibson	327	SI	875	55000000	Ash and Coal Waste	none/natural soils	no liner
Gibson	329	LF	85	20000000	Ash	compacted clay	clay
Gorgas	280	SI	250		Ash and Coal Waste	compacted clay	clay
Gorgas	281	SI	283	24100000	Ash and Coal Waste	compacted clay	clay
Gorgas	282	SI	1500	15000000	Ash and Coal Waste	compacted clay	clay
Green River	147	SI	36	2331219	Ash and Coal Waste	none/natural soils	no liner
Greene County	279	SI	480	5000000	Ash	compacted clay	clay
H B Robinson	169	SI	30		Ash and Coal Waste	none/natural soils	no liner
Hammond	203	SI	56	576256	Ash and Coal Waste	none/natural soils	no liner
Harllee Branch	204	SI	324	7898277	Ash and Coal Waste	none/natural soils	no liner
Harllee Branch	205	SI	203	7634000	Ash and Coal Waste	none/natural soils	no liner
Harrison	211	LF	79	18000000	Ash and Coal Waste	composite clay/membrane	composite
Harrison	330	SI	300	28000000	Ash	none/natural soils	no liner
Hatfield's Ferry	112	LF	20	790000	Ash and Coal Waste	compacted ash	no liner
Hennepin	274	SI	150	3460600	Ash and Coal Waste	none/natural soils	no liner
Heskett	87	LF	58	1550000	FBC	compacted clay	clay
Holcomb	65	LF	8		Ash	compacted ash	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Homer City	118	LF	247	29636550	Ash and Coal Waste	geosynthetic membrane	composite
Hoot Lake	40	LF	72	800000	Ash and Coal Waste	none/natural soils	no liner
Hugo	193	LF	40	4000000	Ash	compacted ash	no liner
Hugo	194	si	151.0232271		Ash and Coal Waste	compacted clay	clay
Hunter	256	LF	280	12000000	Ash	none/natural soils	no liner
Huntington	255	LF	70	11400000	Ash	none/natural soils	no liner
Intermountain	224	SI	105	4840000	Ash and Coal Waste	geosynthetic membrane	composite
Intermountain	225	LF	339	17800000	Ash	compacted ash	no liner
Intermountain	226	SI	180	5200000	Ash	geosynthetic membrane	composite
J H Campbell	115	SI	267	6900000	Ash and Coal Waste	none/natural soils	no liner
J M Stuart	125	SI	88	8357000	Ash	none/natural soils	no liner
J R Whiting	129	SI	6	140000	Ash	none/natural soils	no liner
Jack McDonough	202	SI	73	1531893	Ash and Coal Waste	none/natural soils	no liner
Jack Watson	220	SI	100		Ash	none/natural soils	no liner
James H Miller Jr.	300	SI	200	5500000	Ash	compacted clay	clay
Jim Bridger	257	LF	120	7940941	Ash	none/natural soils	no liner
Jim Bridger	258	LF	241	24000000	Ash and Coal Waste	none/natural soils	no liner
Jim Bridger	259	SI	140	3400000	Ash and Coal Waste	none/natural soils	no liner
Jim Bridger	262	SI	125	6500000	Ash and Coal Waste	none/natural soils	no liner
John E Amos	120	SI	100	13000000	Ash	none/natural soils	no liner
John E Amos	121	LF	200	14000000	Ash and Coal Waste	compacted clay	clay
John E Amos	122	SI	10	3078000	Ash	none/natural soils	no liner
John Sevier	297	SI	57	1600000	Ash and Coal Waste	none/natural soils	no liner
John Sevier	298	LF	51	4800000	Ash	compacted clay	clay
John Sevier	309	SI	105	7000000	Ash and Coal Waste	none/natural soils	no liner
Johnsonville	306	SI	91	2900000	Ash and Coal Waste	none/natural soils	no liner
Joliet 29	275	SI	63.1	1012000	Ash and Coal Waste	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Keystone	106	LF	155	22663120	Ash and Coal Waste	none/natural soils	no liner
Killen Station	254	SI		99935	Ash and Coal Waste	compacted clay	clay
Kingston	311	SI	41	11000000	Ash and Coal Waste	none/natural soils	no liner
Kingston	312	SI	275	8900000	Ash and Coal Waste	none/natural soils	no liner
Kraft	206	si	59.87027428		Ash and Coal Waste	none/natural soils	no liner
L V Sutton	231	SI	162	7696000	Ash and Coal Waste	none/natural soils	no liner
Lansing	64	SI	15		Ash	compacted clay	clay
Laramie R Station	260	SI	10.7	464156	Ash and Coal Waste	compacted clay	clay
Laramie R Station	261	SI	38	939605	Ash	geosynthetic membrane	composite
Lawrence EC	109	LF	825	34300000	Ash	compacted clay	clay
Lawrence EC	110	LF	22	1360000	Ash	compacted clay	clay
Lawrence EC	111	LF	30	1000000	Ash	compacted clay	clay
Lee	240	SI	35	1936000	Ash and Coal Waste	none/natural soils	no liner
Leland Olds	103	LF	37	1800000	Ash	compacted clay	clay
Leland Olds	104	LF	20	458000	Ash and Coal Waste	none/natural soils	no liner
Lon Wright	98	LF		170000	Ash	none/natural soils	no liner
Louisa	63	SI	30	500000	Ash	compacted clay	clay
Marion	52	LF	105	2200000	Ash	none/natural soils	no liner
Marion	53	LF	38	1000000	Ash	compacted clay	clay
Marshall	232	LF	110	7826000	Ash	none/natural soils	no liner
Marshall	233	SI	340	19689000	Ash and Coal Waste	none/natural soils	no liner
Martin Lake	152	LF	290	30000000	Ash	compacted clay	clay
Mayo	171	SI	30	185000	Ash	none/natural soils	no liner
Mayo	172	SI	65	2400000	Ash	none/natural soils	no liner
Meramec	175	SI	61.1	591200	Ash and Coal Waste	none/natural soils	no liner
Merom	184	LF	65	8500000	Ash	none/natural soils	no liner
Miami Fort	39	LF	80	4000000	Ash	compacted clay	clay

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Milton R Young	100	LF	80	6500000	Ash	compacted clay	clay
Mitchell - PA	208	LF	70	5600000	Ash	none/natural soils	no liner
Mitchell - WV	131	SI		12030000	Ash and Coal Waste	none/natural soils	no liner
Mohave	72	LF	250	21500000	Ash	none/natural soils	no liner
Monroe	26	LF	400	20000000	Ash and Coal Waste	none/natural soils	no liner
Monroe	27	SI	400	15000000	Ash	none/natural soils	no liner
Morgantown	291	LF	212	7700000	Ash and Coal Waste	none/natural soils	no liner
Mountaineer (1301)	212	LF	60	9700000	Ash	composite clay/membrane	composite
Mt Storm	73	LF	125	18920000	Ash	composite clay/membrane	composite
Mt Storm	134	LF	900	8800000	Ash and Coal Waste	compacted clay	clay
Muscatine Plant #1	70	LF	36	2000000	Ash	compacted clay	clay
Muskogee	51	LF	36	1247112	Ash	compacted clay	clay
Neal North	92	SI	150		Ash and Coal Waste	none/natural soils	no liner
Neal North	93	LF	200		Ash	none/natural soils	no liner
Neal South	284	LF	150		Ash	none/natural soils	no liner
Nebraska City	20	LF	17	600000	Ash and Coal Waste	compacted clay	clay
New Castle	66	LF	27	1100000	Ash and Coal Waste	geosynthetic membrane	composite
Newton	180	LF	309		Ash	none/natural soils	no liner
North Omaha	17	LF	13	105000	Ash and Coal Waste	compacted clay	clay
Northeastern	142	LF	69	3185190	Ash	none/natural soils	no liner
Nucla	96	LF	41.2	1500000	FBC	none/natural soils	no liner
Oklaunion	228	SI	11	408940	Ash and Coal Waste	none/natural soils	no liner
Oklaunion	229	SI	19.4	718060	Ash	none/natural soils	no liner
Oklaunion	230	SI	290.8	6056820	Ash	none/natural soils	no liner
Paradise	146	SI	85	7582510	Ash	composite clay/membrane	composite
Paradise	316	SI	200	5000000	Ash	none/natural soils	no liner
Petersburg	155	LF	250	19750000	Ash	compacted clay	clay

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Petersburg	156	si	156.6901408		Ash	none/natural soils	no liner
Pleasant Prairie	243	LF	26	6500000	Ash and Coal Waste	geosynthetic membrane	composite
Port Washington	242	LF	300	1900000	Ash and Coal Waste	compacted clay	clay
Portland	67	LF	15	2200000	Ash and Coal Waste	none/natural soils	no liner
Possum Point	77	SI	56		Ash and Coal Waste	none/natural soils	no liner
Potomac River	140	LF	33	802000	Ash	geosynthetic membrane	composite
Presque Isle	116	LF	292	14200000	Ash	none/natural soils	no liner
R Gallagher	326	SI	170	20000000	Ash and Coal Waste	compacted clay	clay
R M Schahfer	84	SI	80	1030000	Ash and Coal Waste	none/natural soils	no liner
R M Schahfer	85	LF	200	17200000	Ash	none/natural soils	no liner
Reid Gardner	95	LF	112.5	4520000	Ash	none/natural soils	no liner
Richard Gorsuch	36	LF		3003600	Ash	compacted clay	clay
Riverbend	165	SI	143	3200000	Ash	none/natural soils	no liner
Rodemacher	247	SI	36	1200000	Ash	compacted clay	clay
Rodemacher	248	SI	109	2500000	Ash	compacted clay	clay
Roxboro	239	LF	55	4165000	Ash	none/natural soils	no liner
Sandow	153	LF	125	1300000	Ash	compacted clay	clay
Sandow	187	LF	48	903467	Ash and Coal Waste	none/natural soils	no liner
Sandow	188	SI	45	1351973	Ash and Coal Waste	none/natural soils	no liner
Scherer	199	SI	490	22262030	Ash and Coal Waste	none/natural soils	no liner
Shawnee	317	SI	180	5810000	Ash and Coal Waste	none/natural soils	no liner
Shawnee	318	LF	96	6100000	FBC	none/natural soils	no liner
Shawville	209	LF	68	8000000	Ash	none/natural soils	no liner
Sheldon	23	LF	9	375000	Ash	compacted clay	clay
South Oak Creek	3	LF	45	4050000	Ash and Coal Waste	compacted clay	clay
South Oak Creek	4	LF	130	4600000	Ash	none/natural soils	no liner
Springerville	154	LF	57	6400000	Ash	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
St Johns River Power	158	lf	128.624166		Ash and Coal Waste	compacted clay	clay
Stanton Energy Ctr.	117	LF	312		Ash	none/natural soils	no liner
Stockton Cogen Company	2000	LF	4	533333	FBC	composite clay/membrane	composite
Syl Laskin	68	SI	75	726000	Ash and Coal Waste	none/natural soils	no liner
Tecumseh EC	177	LF	540		Ash	compacted clay	clay
Texas-New Mexico	3900	LF	61	6142473	FBC	compacted clay	clay
Titus	207	LF	39	3000000	Ash and Coal Waste	composite clay/membrane	composite
Trimble County	69	SI	115	6856667	Ash	compacted clay	clay
Tyrone	148	SI	5.5	351699	Ash	none/natural soils	no liner
Tyrone	149	SI	5	327500	Ash and Coal Waste	none/natural soils	no liner
Tyrone	150	SI	7.75	500123	Ash and Coal Waste	none/natural soils	no liner
Valley	8	LF	16.4	534000	Ash and Coal Waste	compacted clay	clay
Vermilion	55	SI	43	8100000	Ash and Coal Waste	none/natural soils	no liner
Victor J Daniel Jr	287	lf	49.20163084		Ash	compacted clay	clay
Victor J Daniel Jr	288	si	20.03879417		Ash and Coal Waste	composite clay/membrane	composite
W A Parish	189	lf	28.68322214		Ash	compacted clay	clay
W H Weatherspoon	236	SI	26	1200000	Ash and Coal Waste	none/natural soils	no liner
W S Lee	238	SI	41	1634000	Ash and Coal Waste	none/natural soils	no liner
Wabash River	324	SI	120	14000000	Ash and Coal Waste	none/natural soils	no liner
Walter C Beckjord	123	LF	14	1000000	Ash	compacted ash	no liner
Walter C Beckjord	124	SI		2000000	Ash	none/natural soils	no liner
Wansley	200	SI	330	18712850	Ash and Coal Waste	none/natural soils	no liner
Wansley	201	SI	43		Ash	none/natural soils	no liner
Warrick	181	SI	140	4500000	Ash and Coal Waste	compacted clay	clay
Waukegan	54	LF	60	4000000	Ash and Coal Waste	compacted clay	clay
Weston	241	LF	18	600000	Ash	none/natural soils	no liner
Widows Creek	320	SI	110	3500000	Ash and Coal Waste	none/natural soils	no liner

(continued)

CCW WMU Data (continued)

Plant	Facility ID	WMU Type	Area (acres)	Capacity (cubic yards)	Waste Type	Original Liner	Liner Type
Widows Creek	321	SI	222	12400000	Ash	compacted clay	clay
Will County	277	SI	60	599256	Ash and Coal Waste	compacted clay	clay
Wyodak	71	LF	68	3500000	Ash	geosynthetic membrane	composite
Yates	197	SI	4.7	115000	Ash	composite clay/membrane	composite

Appendix C. Site Data

The site characteristics used in this analysis were based on site-specific, regional, and national data sources to provide the environmental parameters necessary for modeling the fate and transport of coal combustion waste (CCW) constituents released in landfill or surface impoundment leachate. Site-specific data were collected for the area in the immediate vicinity of the waste management unit (WMU), and included the geographic relationship among important features such as the WMU boundary, residential well location, and streams and lakes. These data were collected at each of the 181 coal-fired power plants selected for the analysis. These 181 locations across the continental United States are intended to represent the geographic distribution of onsite WMUs used for disposal of CCW and were used to capture national variability in meteorology, soils, climate, aquifers, and surface waterbodies at the disposal sites.

C.1 Data Collection Methodology

The CCW risk assessment employed a site-based data collection method. This method used the CCW plant locations from the Energy Information Administration (EIA) database to obtain data for each facility that were representative of the environment immediately surrounding the plant. Depending on the availability of information, data were collected on either a site-specific, regional, or national scale. Where appropriate, distributions were used in the Monte Carlo analysis to capture site-to-site and within-site variability in the parameters collected.

Site-based data were collected using a geographic information system (GIS) that allowed (1) site-specific data to be assembled from the area immediately surrounding the facility and (2) the site to be assigned to a region to collect regional data. To account for locational uncertainty for the CCW WMUs[1], a 5-km radius was used to define the data collection area for aquifer type and soil data. If multiple soil or aquifer types occurred within this radius, multiple types were sent to the model, weighted by the fraction of the collection area that they occupied. Surface waterbody type and stream flows also were collected for each site by identifying the nearest stream segment.

Climate and water quality data were collected by assigning each site to a meteorological station and a U.S. Geological Survey (USGS) hydrologic region. The EPA STOrage and RETrieval (STORET) database was used as the source for water quality data, with parameters selected from distributions queried from this database for each region.

Because the EIA locations were not exact for the WMUs being modeled, a national distribution of stream distances was developed by manually measuring the distance between the WMU and the waterbody at a random sample of the CCW sites. Similarly, a national distribution

[1] The EIA latitudes and longitudes usually represent a facility centroid or front-gate location for each power plant. Because these facilities are often large, the WMUs are frequently located some distance from the plant itself and not at the EIA location.

was used to represent the distance of the nearest residential wells from the CCW WMUs being modeled.

C.2 Receptor Location (National Data)

The residential scenario for the CCW groundwater pathway analysis calculates exposure through use of well water as drinking water. During the Monte Carlo analysis, the receptor well is placed at a distance of up to 1 mile from the edge of the WMU, by sampling a nationwide distribution of nearest downgradient residential well distances taken from a survey of municipal solid waste landfills (U.S. EPA, 1988).

EPA believes that this MSW well-distance distribution (presented in Table C-1) is protective for onsite CCW landfills and surface impoundments at coal-fired utility power plants, but recognizes that this is a significant uncertainty in this analysis. Because CCW plants tend to be in more isolated areas than MSW landfills and because CCW WMUs tend to be larger than municipal landfills, EPA believes that the MSW well distance distribution is a conservative representation of actual well distances at CCW disposal sites. However, data on residential well distances from CCW landfills or surface impoundments will be needed to verify this hypothesis.

As discussed in Section 3.4.3, the groundwater model used in the CCW risk assessment places limits on the lateral direction from the plume centerline (i.e., angle off plume centerline) and depth below the water table to ensure that the well remains within the plume and at a depth appropriate for surficial aquifers across the United States. These limits are consistent with other recent national risk assessments conducted by EPA OSW and provide a protective approach to siting wells for this analysis.

Table C-1. Distribution of Receptor Well Distance

Percentile	x-distance (m)
Minimum	0.6
10	104
20	183
30	305
40	366
50 (Median)	427
60	610
70	805
80	914
90	1,220
Maximum	1,610

Source: U.S. EPA (1988).

C.2.1 Recreational Fisher and Ecological Risk Scenario (Distance to Waterbody)

The recreational fisher scenario was used to estimate risks to recreational fishers and their children who live in the vicinity of the CCW landfills and surface impoundments and catch and

consume fish from a waterbody located adjacent to the buffer. The waterbody was assumed to be a stream or lake located downwind of the WMU, beginning where the buffer area ends (see Figure 2-4), and was also used as the reasonable worst case aquatic system for the ecological risk assessment. Waterbody characteristics were determined based on site-specific, regional, or national data (as described in Section C.6), except for stream length, which was determined by the width of the plume as it intersects the waterbody.

The downgradient distance to the surface water body was determined from a national distribution developed by measuring this distance at 59 CCW landfill and surface impoundment sites randomly selected from the 204 WMUs modeled in this risk assessment. Table C-2 presents this distribution. Figure C-1 provides a map and aerial photo of one of the facilities used to develop this distribution. The development of this distribution is described in Section C.6.4.

Table C-2. Distribution of Surface Water Distances

Percentile	Distance (m)
Minimum	10
0.03	10
0.05	20
0.07	20
0.09	20
0.10	20
0.13	20
0.15	30
0.20	40
0.25	50
0.30	50
0.35	60
0.40	70
0.45	100
0.50 (Median)	120
0.55	130
0.60	150
0.65	250
0.70	400
0.75	440
0.80	500
0.85	700
0.87	775
0.90	800
0.91	1,000
0.93	1,500
0.95	2,125
0.97	2,750
Maximum	3,000

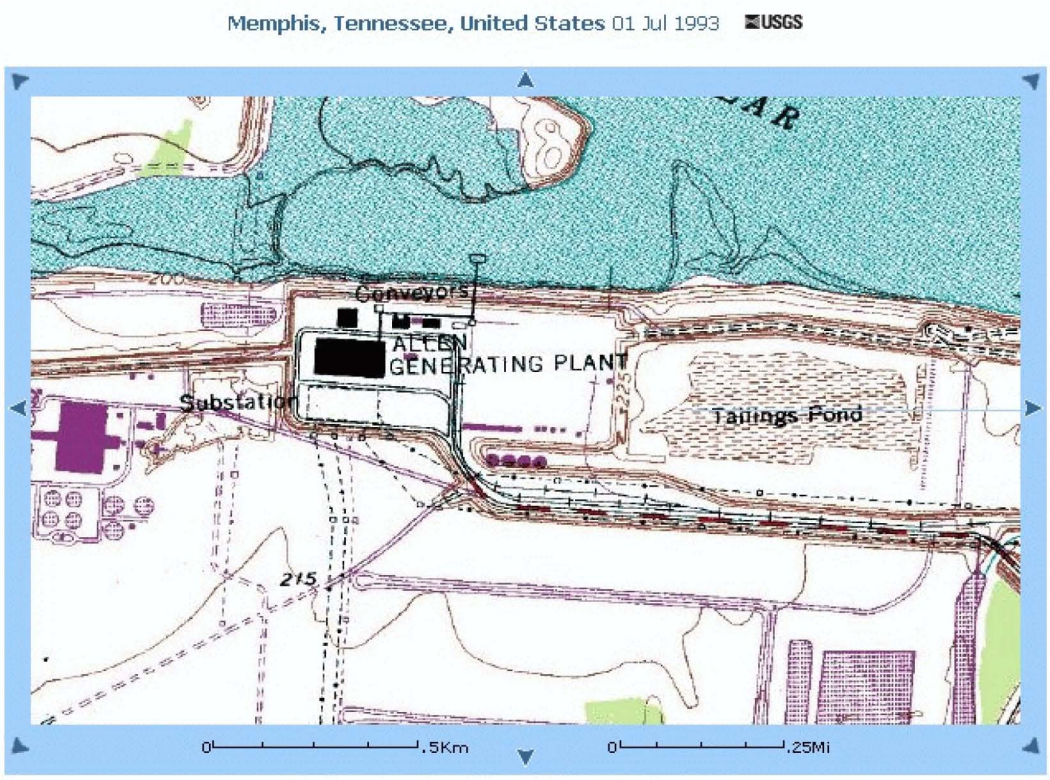

Image courtesy of the U.S. Geological Survey

Image courtesy of the U.S. Geological Survey

Figure C-1. Example CCW site used to develop waterbody distance distribution.

C.3 Soil Data

The groundwater model used in the CCW risk assessment—EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP)—requires soil properties for the entire soil column to model leachate transport through the vadose zone to groundwater. As with aquifer type, soil data were collected within a 5-km radius of each CCW plant. A GIS was used to identify soil map units within a 20-mile radius around each meteorological station. Database programs were then used to assemble and process soil texture, pH, and soil organic matter data for these map units from the State Soil Geographic (STATSGO) database. Both pH and soil organic matter were processed and indexed by the soil textures present within the 5-km radius. Soil properties are listed by texture for each of the 181 CCW plants in Attachment C-1.

C.3.1 Data Sources

The primary data source for soil properties was the STATSGO database. STATSGO is a repository of nationwide soil properties compiled primarily by the U.S. Department of Agriculture (USDA) from county soil survey data (USDA, 1994). STATSGO includes a 1:250,000-scale GIS coverage that delineates soil map units and an associated database containing soil data for each STATSGO map unit. (Map units are areas used to spatially represent soils in the database.)

In addition, two compilations of STATSGO data, each keyed to the STATSGO map unit GIS coverage, were used in the analysis as a convenient source of average soil properties:

- **USSOILS.** The USSOILS data set (Schwarz and Alexander, 1995) averages STATSGO data over the entire soil column for each map unit.
- **CONUS.** The Conterminous United States Multi-Layer Soil Characteristics (CONUS) data set (Miller and White, 1998) provides average STATSGO data by map unit and a set of 11 standardized soil layers.

Soil organic matter and pH were derived directly from USSOILS and STATSGO data. A complete set of hydrological soil properties[2] was not available from STATSGO. To ensure consistent and realistic values, EPACMTP relies on established, nationwide relationships between hydrologic properties and soil texture. Peer-reviewed publications by Carsel and Parrish (1988) and Carsel et al. (1988) provide a consistent set of correlated hydrologic properties for each soil texture. Soil texture data for the entire soil column were collected from the CONUS database.

C.3.2 Methodology

The soil data collection methodology begins with GIS programs (in Arc Macro Language [AML]). These programs overlay a 5-km radius around each CCW plant location on the STATSGO map unit coverage to determine the STATSGO map units and their area within the radius. These data are then passed to data processing programs that derive soil properties for

[2] Hydrological soil properties required by EPACMTP include bulk density, saturated water content, saturated hydraulic conductivity, and the van Genuchten soil moisture retention parameters alpha and beta.

each site, either through direct calculations or by applying established relationships in lookup tables.

EPACMTP utilizes three soil textures to represent variability in hydrologic soil properties and (along with climate data) to assign infiltration rates to each site. Because STATSGO soils are classified into the 12 U.S. Soil Conservation Service (SCS) soil textures, the crosswalk shown in Table C-3 was used to assign the SCS textures to the EPACMTP megatextures and to calculate the percentage of each megatexture within the 5-km data collection radius. These percentages were sampled for each site when preparing the source data file for each site.

Both soil pH and soil organic matter were derived for each EPACMTP soil megatexture at a site. During source data file preparation, when a megatexture was picked for a particular iteration of a site, the corresponding pH and organic matter values were selected as well.

Table C-3. EPACMTP Soil Texture Crosswalk

STATSGO Texture	EPACMTP Megatexture
Sand	Sandy loam
Loamy sand	
Sandy loam	
Silt loam	Silt loam
Silt	
Loam	
Sandy clay loam	
Clay loam	
Silty clay loam	Silty clay loam
Sandy clay	
Silty clay	
Clay	

C.3.3 Results

Attachment C-1 lists the STATSGO soil textures and EPACMTP megatexture assignments and percentages for each CCW disposal site.

C.4 Hydrogeologic Environments (Aquifer Type)

To assign aquifer properties used by EPACMTP, it was necessary to designate hydrogeologic environments (or aquifer types) for each of the locations modeled so that correlated, national aquifer property data could be used in the analysis. EPACMTP uses the Hydrogeologic Database (HGDB) developed by the American Petroleum Institute (API) (Newell et al., 1989; Newell et al., 1990) to specify correlated probability distributions, which are used to populate the following four hydrogeologic parameters during the Monte Carlo analysis:

- Unsaturated zone thickness
- Aquifer thickness

- Hydraulic gradient
- Saturated hydraulic conductivity.

The HGDB provides correlated data on these hydrogeologic parameters and an aquifer classification for approximately 400 hazardous waste sites nationwide, grouped according to 12 hydrogeologic environments described in Newell et al. (1990). The *EPACMTP User's Guide* (U.S. EPA, 1997) provides the empirical distributions of the four hydrogeologic parameters for each of the hydrogeologic environments.

Average aquifer/vadose zone temperature was also required for the groundwater model and was obtained from a digitized map of groundwater temperatures for the continental United States from the *Water Encyclopedia* (van der Leeden et al., 1990).

The hydrogeologic environment approach to assigning EPACMTP aquifer variables relies upon a hydrogeologic framework originally developed for an attempt by EPA to classify and score groundwater environments according to their potential to be polluted by pesticide application. Although this DRASTIC[3] scoring system was not widely applied to determining groundwater vulnerability to pesticide pollution, the hydrogeologic framework established for the effort has proven very useful in categorizing geologic settings in terms of the aquifer characteristics needed for groundwater modeling. The major components of this modeling framework are Groundwater Regions, hydrogeologic settings, and hydrogeologic environments, as described below:

- The fifteen **Groundwater Regions**, defined by Heath (1984), provide a regional framework that groups hydrogeologic features (i.e., nature and extent of dominant aquifers and their relationship to other geologic units) that influence groundwater occurrence and availability.

- **Hydrogeologic settings** were developed within each Heath region by Aller et al. (1987)[4] to create mappable geological units that are at the proper scale to capture differences in aquifer conditions. Note that there may be the same or similar settings across different regions (e.g., the alluvial settings). Within each region, Aller et al. (1987) describe each setting with a written narrative and provide a block diagram to visualize the geology, geomorphology, and hydrogeology.

- **Hydrogeologic environments** were developed by Newell et al. (1990) as the geologic framework for the API's HGDB. To create the 12 environments, Newell et al. rolled up similar hydrologic settings across the Groundwater Regions to group settings with similar aquifer characteristics (hydraulic conductivity, gradient, thickness, and depth-to-water). Table C-4 shows the crosswalk between hydrologic environment and hydrogeologic setting, organized by Groundwater Region.

[3] The DRASTIC scoring factors are Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone media, and aquifer hydraulic Conductivity.

[4] Aller et al. (1987, p. 14) did not develop settings for Region 15 (Puerto Rico and the Virgin Islands) and reincorporated Region 12 (Alluvial Valleys) into each of the other regions as "river alluvium with overbank deposits" and "river alluvium without overbank deposits."

Because EPACMTP utilizes the HGDB for national and regional analyses (using a regional site-based approach), it was necessary to assign the CCW sites to a hydrogeologic environment so that the correct HGDB data set will be used for modeling each site. The data sources and methodology used to make these assignments are described below.

C.4.1 Data Sources

Data sources used to make hydrogeologic assignments for the sites include:

- A USGS inventory of state groundwater resources (Heath, 1985)
- GIS coverages from *Digital Data Sets Describing Principal Aquifers, Surficial Geology, and Ground-Water Regions of the Conterminous United States* (Clawges and Price, 1999a-d)
- GIS coverages of principal aquifers from the USGS *Groundwater Atlas* (Miller, 1998)
- STATSGO soil texture data (described in Section C.3.2).

These coverages were used in a GIS overlay process to determine the principal aquifers, surficial geologic units, groundwater region, productive aquifers, and general hydrogeologic settings for a 5-km radius around each CCW facility location. Attributes for each of these items were passed to a database for use in assigning hydrogeologic environments.

C.4.2 Assignment Methodology

For each CCW site, hydrogeologic environments were assigned by a professional geologist as follows:

- Determine Heath Groundwater Region (for the Alluvial Valleys region, determine the region in which the alluvial valley is located)
- Assign hydrogeologic setting using state geological descriptions from Heath (1985); aquifer, soil, and surficial geology information obtained using GIS; and narratives and block diagrams from Aller et al. (1987)
- Using the look-up table from Newell et al. (1990), determine hydrogeologic environment from hydrogeologic setting.

In general, the surficial geology coverage had better resolution than the aquifer coverages and was used to develop setting percentages for the 5-km radius. In most cases, there were two settings per site. In cases where a single setting accounted for over 80 percent of the 5-km area, a single setting was assigned.

Because Newell et al. (1990) define two alluvial environments (6, River alluvium with overbank deposits, and 7, River alluvium without overbank deposits), it was necessary to determine which environment an alluvial site fell into. The survey soil layer information was used to distinguish between these two settings by determining whether there were significant fine-grained overbank deposits in the soil column.

Quality assurance/quality control (QA/QC) measures included independent review of the assignments by other geologists with expertise in assigning settings.

C.4.3 Data Processing

HGDB hydrogeologic environment fractions (i.e., the portion of the region assigned to each of the 12 hydrogeological environments) were defined and used in the CCW risk assessment as follows. If the 5-km radius around a site contained only one HGDB environment, the fraction assigned was 1.0 and all groundwater model runs for this location were associated with that hydrological environment. If more than one HGDB environment was present, each environment was assigned a fraction based on the areal percentages of each setting within the 5-km radius.

These fractions were used to generate the hydrogeologic environment for that location for each iteration of the Monte Carlo groundwater modeling analysis. For example, if two hydrogeologic environments were assigned to a CCW site with a fraction of 0.5, half of the realizations would be modeled with the first hydrogeologic environment and half with the second.

Once the hydrogeologic environments were assigned, a preprocessing run of EPACMTP was conducted to construct a set of randomly generated but correlated hydrogeologic parameter values for each occurrence of the hydrogeologic environments in the source data files. Missing values in the HGDB data set were filled using correlations, as described in U.S. EPA (1997).

C.4.4 Results

Attachment C-2 lists the hydrogeologic environment assignments for each CCW disposal site. Table C-4 summarizes these results showing the crosswalk between Groundwater Regions, hydrogeologic settings, and hydrogeologic environments used to make the assignments, along with the number of CCW sites for each setting. Table C-5 totals the number of CCW disposal sites for each hydrogeologic environment sent to EPACMTP.

Table C-4. Groundwater Regions, Hydrogeologic Settings, and Hydrogeologic Environments: CCW Disposal Sites

Hydrogeologic Setting		Hydrogeologic Environment	Number of CCW Sites
Alluvial Basins			
2C	Alluvial Fans	5	1
2E	Playa Lakes	5	1
2Ha	River Alluvium With Overbank Deposits	6	1
Colorado Plateau and Wyoming Basin			
4B	Consolidated Sedimentary Rock	2	7
4C	River Alluvium	7	3
High Plains			
5Gb	River Alluvium Without Overbank Deposits	7	1

(continued)

Table C-4. (continued)

Hydrogeologic Setting		Hydrogeologic Environment	Number of CCW Sites
Nonglaciated Central Region			
6Da	Alternating Sandstone, Limestone, and Shale – Thin Soil	2	22
6Db	Alternating Sandstone, Limestone, and Shale – Deep Regolith	2	6
6E	Solution Limestone	12	9
6Fa	River Alluvium With Overbank Deposits	6	37
6Fb	River Alluvium Without Overbank Deposits	7	4
6H	Triassic Basins	2	4
Glaciated Central Region			
7Aa	Glacial Till Over Bedded Sedimentary Rock	3	12
7Ac	Glacial Till Over Solution Limestone	12	6
7Ba	Outwash	8	1
7Bb	Outwash Over Bedded Sedimentary Rock	2	3
7Bc	Outwash Over Solution Limestone	12	2
7D	Buried Valley	4	11
7Ea	River Alluvium With Overbank Deposits	6	24
7Eb	River Alluvium Without Overbank Deposits	7	6
7F	Glacial Lake Deposits	4	3
7G	Thin Till Over Bedded Sedimentary Rock	3	5
7H	Beaches, Beach Ridges, and Sand Dunes	11	1
Piedmont and Blue Ridge			
8B	Alluvial Mountain Valleys	5	1
8C	Mountain Flanks	2	2
8D	Regolith	1	13
8E	River Alluvium	6	6
Northeast and Superior Uplands			
9E	Outwash	8	3
9F	Moraine	4	1
9Ga	River Alluvium With Overbank Deposits	6	1
Atlantic and Gulf Coastal Plain			
10Aa	Regional Aquifers	4	1
10Ab	Unconsolidated/Semiconsolidated Shallow Surficial Aquifers	10	20
10Ba	River Alluvium With Overbank Deposits	6	7
10Bb	River Alluvium Without Overbank Deposits	7	6
Southeast Coastal Plain			
11A	**Solution Limestone and Shallow Surficial Aquifers**	**12**	**3**
11B	**Coastal Deposits**	**4**	**1**

Table C-5. Hydrogeologic Environments for CCW Disposal Sites

Hydrogeologic Environment		Number of CCW Sites
1	Metamorphic and Igneous	13
2	Bedded Sedimentary Rock	44
3	Till Over Sedimentary Rock	17
4	Sand and Gravel	17
5	Alluvial Basins Valleys and Fans	3
6	River Valleys and Floodplains With Overbank Deposit	76
7	River Valleys and Floodplains Without Overbank Deposits	20
8	Outwash	4
9	Till and Till Over Outwash	0
10	Unconsolidated and Semiconsolidated Shallow Aquifers	20
11	Coastal Beaches	1
12	Solution Limestone	20

C.5 Climate Data

The CCW risk assessment selected EPACMTP meteorological (or climate) stations for each CCW disposal site to collect the climatic data necessary for fate and transport modeling. For each station, the following data were compiled:

- Mean annual windspeed
- Mean annual air temperature
- Mean annual precipitation.

With respect to precipitation, EPACMTP uses the climate station, along with soil texture, to select the HELP- (Hydrologic Evaluation of Landfill Performance-) modeled infiltration rates to use in the landfill source model and recharge rates to use in EPACMTP (see Section 3.2.2). The surface water model uses mean annual windspeed and average air temperature to estimate volatilization losses from the surface waterbodies modeled in the analysis.

To assign the EPACMTP climate centers to each CCW site, a GIS was used to determine the three meteorological stations closest to the plant. These assignments were passed to a meteorologist, who reviewed the closest stations against plots of the CCW sites and the climate centers on a downloadable map (http://www.nationalatlas.gov/prismmt.html) of annual average precipitation rates for the period from 1961 to 1990 across the contiguous United States. (Figure C-2). The meteorologist compared the 5-year average precipitation range for each EPACMTP climate center to precipitation ranges for each plant from the map. In most cases, the precipitation rate for the nearest climate center fell within the site's expected precipitation range, and the nearest climate center was assigned in those cases. In some cases, the precipitation rates from the nearest climate center did not fall within the site's expected range. When this occurred, the second or third closest climate center was examined and matched based on:

- A 5-year precipitation average within or close to the site's predicted precipitation range

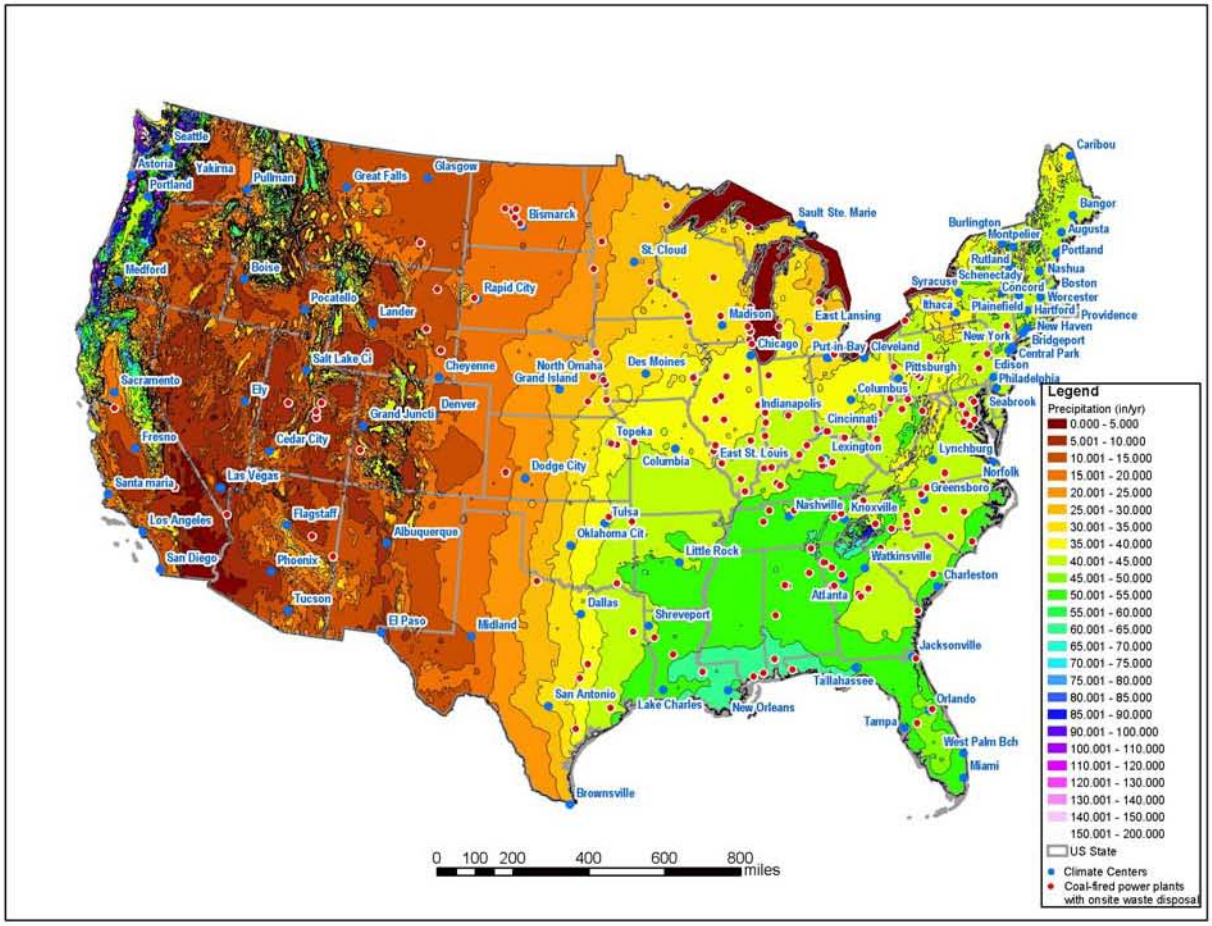

Figure C-2. EPACMTP climate centers, precipitation ranges, and CCW disposal sites.

- Confirmation of a site's average annual rainfall on http://www.weather.com and van der Leeden et al. (1990)
- Geographic similarities between plant and climate center locations
- Best professional judgment.

In a few cases, the three closest climate centers did not reflect the average precipitation rates for a plant's location. In these cases, other nearby stations were examined and the plant was assigned to the closest climate center with similar geography and average precipitation rates. Each assignment was independently checked for accuracy. Attachment C-3 lists the climate center assigned to each CCW disposal site, along with notes for plants not assigned to the nearest center. Table C-6 lists all the climate centers used in the CCW risk assessment along with the number of CCW sites assigned to each station.

Table C-6. EPACMTP Climate Centers Assigned to CCW Disposal Sites

Climate Center		State	Number of CCW Sites
4	Grand Junction	CO	2
6	Glasgow	MT	1
7	Bismarck	ND	5
10	Cheyenne	WY	2
11	Lander	WY	1
13	Sacramento	CA	1
16	Ely	NV	1
17	Rapid City	SD	2
18	Cedar City	UT	1
19	Albuquerque	NM	1
20	Las Vegas	NV	3
21	Phoenix	AZ	1
26	Salt Lake City	UT	1
29	Dodge City	KS	1
31	St. Cloud	MN	3
32	East Lansing	MI	3
33	North Omaha	NE	7
34	Tulsa	OK	2
37	Oklahoma City	OK	1
39	Pittsburgh	PA	12
42	Chicago	IL	8
48	Sault Ste. Marie	MI	1
49	Put-in-Bay	OH	3
50	Madison	WI	9
51	Columbus	OH	2
53	Des Moines	IA	2
54	East St. Louis	IL	8
55	Columbia	MO	1
56	Topeka	KS	3
58	San Antonio	TX	4
66	Ithaca	NY	1
69	Lynchburg	VA	2
71	Philadelphia	PA	2
72	Seabrook	NJ	5
73	Indianapolis	IN	12
74	Cincinnati	OH	11
75	Bridgeport	CT	1
76	Orlando	FL	2
77	Greensboro	NC	11

(continued)

Table C-6. (continued)

Climate Center		State	Number of CCW Sites
78	Jacksonville	FL	1
79	Watkinsville	GA	4
80	Norfolk	VA	2
81	Shreveport	LA	4
85	Knoxville	TN	4
87	Lexington	KY	3
89	Nashville	TN	4
90	Little Rock	AR	1
91	Tallahassee	FL	4
93	Charleston	SC	4
95	Atlanta	GA	9
96	Lake Charles	LA	2

C.6 Surface Water Data

The surface water model used in the CCW risk assessment requires information on surface waterbody type (river or lake), flow conditions, dimensions, and water quality. In addition, the groundwater model requires the distance between the waterbody and the WMU being modeled. Surface waterbody data were collected on a site-based, regional, or national basis depending on the variable and data availability. Collection methods are described below by data source. Attachment C-4 provides a summary of waterbody assignments, waterbody types, and flow conditions.

C.6.1 Waterbody Type, Stream Flow Conditions, and Dimensions

Waterbody type and flow parameters were obtained by matching the CCW plants to stream segments in the Reach File Version 1.0 (RF1) database (U.S. EPA, 1990). Stream flow estimates for all RF1 flowing reaches were estimated in the early 1980s. Statistics developed for each flowing reach are mean annual flow, low flow (approximately 7Q10[5]), and mean monthly flow. RF1 also contains velocities corresponding to mean annual and low flow, estimated from a compendium of time-of-travel studies. For streams and rivers, the CCW risk assessment used the low flow statistic and the corresponding flow velocity, along with a waterbody type also included in the RF1 database. All RF1 data are indexed by USGS cataloging unit and stream segment (CUSEG).

To assign the CCW plants to the nearest downgradient reach (i.e., the nearest waterbody in the direction of groundwater flow), a GIS was used to identify the closest RF1 stream segment to each CCW plant location. Because of several uncertainties in the nearest reach approach (i.e., inaccurate WMU location, unknown direction of groundwater flow, and limited lake coverages), the CCW plants also were matched to standard industrial classification (SIC) code 4911 facilities

[5] The minimum 7-day average flow expected to occur within a 10-year return period (i.e., at least once in 10 years).

in EPA's Permit Compliance System (PCS) database (http://www.epa.gov/enviro/html/pcs/index.html), to obtain the PCS information (e.g., name, CUSEG) on the receiving waterbody for the plants' National Pollutant Discharge Elimination System (NPDES) discharge point(s). When the two sources matched, the reach was selected for modeling. When they differed, the PCS data were used, because it was judged more likely that the NPDES receiving waterbody would also be receiving loads from the WMU through the groundwater-to-surface-water pathway. CCW plants that could not be matched to the PCS database were simply assigned the nearest RF1 waterbody.

The next step in the assignment process was to review the waterbody names (especially those from PCS) to identify lakes and reservoirs. Finally, visual review, using aerial photos and topographic maps from the Terraserver Web site (http://terraserver.usa.com), was used to check all low-flow streams and RF1 reaches whose identity was not clear. Attachment C-4 provides the RF1 stream assignments, flows, and waterbody types for the CCW disposal sites.

With respect to waterbody type, the RF1 data include several types of waterbodies, including streams and rivers, and types with zero flows such as lakes, Great Lakes, wide rivers, and coastline features. Each of these waterbody types needed to be designated as a river or a lake for the simple waterbody model used in the full-scale CCW risk assessment. Because only the streams and rivers have flow data in RF1 (i.e., are flowing reaches), all other types were assigned to the lake modeling category. Modeling these features as a simple model lake is a considerable uncertainty in the CCW risk assessment and risk results for these waterbodies should be regarded as preliminary until a more sophisticated surface water model can be parameterized for these special cases. Table C-7 lists the RF1 waterbody types for the waterbodies assigned to the CCW disposal sites, along with the number of CCW plants assigned to each type and the crosswalk to the river (R) or lake (L) waterbody type used in this risk assessment.

Table C-7. RF1 Reach Types Assigned to CCW Disposal Sites

RF1 Code	RF1Name	Description	Reach Model Type[a]	Number of CCW Plants
Flowing Reaches				
M	Artificial Open Water Reach	An artificial reach within any open water, other than a lake or reservoir, to provide connection between input and output reaches of the open water.	R	1
R	Regular Reach	A reach that has upstream and downstream reaches connected to it and that is not classified as another type of reach.	R	106
S	Start Reach	A headwater reach that has no reaches above it and either one or two transport reaches connected to its downstream end.	R	16
T	Terminal Reach	A reach downstream of which there is no other reach (for example, a reach that terminates into an ocean, a land-locked lake, or the ground). This type of reach has either one or two reaches connected to its upstream end.	R	2

(continued)

Table C-7. (continued)

RF1 Code	RF1Name	Description	Reach Model Type[a]	Number of CCW Plants
Reaches with Zero RF1 Flow				
C	Coastal/Continental Shoreline Segment	A reach that represents a segment of a shoreline of a gulf, sea, or ocean.	L	3
G	Great Lakes Shoreline Segment	A reach that represents a segment of a shoreline of the Great Lakes.	L	12
L	Lake Shoreline Segment	A segment that follows the shoreline of a lake other than one of the Great Lakes.	L	36
W	Wide-River Shoreline Segment	A reach that represents a segment of the left or right bank of a stream.	L	5

[a] R = river; L = lake.

Stream dimensions were calculated from the flow data as follows. First, the length of the modeled stream segment was set to be the width of the groundwater plume as it enters the waterbody. Stream width was then determined from flow (Q) using a liner regression equation derived from empirical data by Kocher and Sartor (1997):

$$Width = 5.1867Q^{0.4559} \tag{C-1}$$

Water column depth (dwc) was derived from width, velocity (V), and flow using the continuity equation:

$$dwc = \frac{Q}{v \times Width} \tag{C-2}$$

C.6.2. Lake Flow Conditions and Dimensions

Areas and depths for many of the lakes assigned to the CCW plant sites were not readily available from RF1, Reach File Version 3 (RF3), the National Hydrography Dataset (NHD), or other sources. In addition, many plants are located on very large waterbodies (e.g., the Great Lakes, wide rivers, or coastlines) where applying the simple steady-state, single-compartment model used in this analysis to the entire lake would not be appropriate. For these reasons, a model lake approach was used to represent all lakes and other nonflowing waterbodies assigned to the CCW disposal site.

The model lake chosen was Shipman City Lake in Illinois, a well-characterized 13-acre lake that EPA has chosen as the index reservoir for modeling drinking water exposures to pesticides (Jones et al., 1998). The parameter values shown in Table C-8 for Shipman City Lake were used to model all lakes in this initial analysis. Given that many of the lakes assigned to CCW plants are much larger than 13 acres, this will produce conservative risk results. However, given that many of the plants are located on very large waterbodies, this necessary simplification is one of the largest uncertainties in defining the environmental settings for the CCW risk

assessment. Options can be developed to more accurately parameterize and model such large nonflowing waterbodies.

Table C-8. Model Lake Used in CCW Risk Assessment

Parameter	Value
Area [a]	13 acres
Water column depth (dwc)[a]	9 feet
Hydraulic residence time (HRT)	Random, triangular distribution: Minimum = 1 month Mean = 6 months Maximum = 24 months
Annual flow mixing volume	= (Area × dwc) / HRT

[a] Source: Shipman City Lake, IL (Jones et al., 1998).

C.6.3 Water Quality Data

Surface water temperature, total suspended solids (TSS), and pH data were collected by USGS hydrologic region from the STORET database. EPA's STORET system is the largest single source of water quality data in the country. The Legacy STORET database contains over 275 million analyses performed on more than 45 million samples collected from 800,000 stations across the United States for the period 1960 through 1998. STORET can be accessed from the Web at http://www.epa.gov/OWOW/STORET.

STORET water quality data are notoriously "noisy" because they are influenced by hydrology, point sources, nonpoint sources, stream/lake morphology, and varying data quality. The following issues in using STORET data must be considered before using the data:

- Not all of the data have undergone rigorous QA/QC.
- STORET site locations can be biased, especially to known "problem" waters.
- The sample times are often at critical periods, such as summer low flows.

Statistical analysis techniques were employed taking into account the above issues (including coordination with gage statistical analysis and Reach Files, the use of median values to avoid bias in central tendency estimates, and specification of a minimum number of measurements to estimate median values). As a result of these techniques, which can be thought of as extracting the underlying "signal" of water quality from the inherent "noise" of water quality data, the above issues were manageable.

Surface water temperature data were collected as median values for each hydrologic region. These data are shown in Table C-9 along with the number of the modeled CCW plants in each region.

Table C-9. Regional Surface Water Temperatures: CCW Disposal Sites

Hydrologic Region	Surface Water Temperature (°C)	Number of CCW Plants
2	16	12
3	21	37
4	14	14
5	17	43
6	18	6
7	15	20
8	20	2
9	10	1
10	13	20
11	17	8
12	21	6
14	9	5
15	17	4
16	9	1
18	15	2

Data source: Legacy STORET database.

Total suspended solids data were collected separately for streams/rivers and lakes because lakes tend to have lower TSS levels. Annual median values were used to develop statistics. For rivers, the minimum, maximum, and geometric mean values were used to define log triangular distributions for each hydrologic region (Table C-10); these distributions were then sampled during the preparation of the source data files. (The geometric means were weighted by the annual number of measurements.) For lakes, data were limited and national statistics were developed, with the geometric mean of the median values being weighted by the number of measurements per year and the number of annual values in each region.

Table C-10. Surface Water Total Suspended Solids (TSS) Distributions

Hydrologic Region	Number of CCW Plants	No. of Measure-ments	No. of Annual Medians	Annual Median TSS (log triangular distribution)			Geometric Mean
				Minimum	Maximum	Weighted Geometric Mean	
1	0	9,007	33	3.2	40	8.0	6.0
2	12	47,202	38	10	316	32	40
3	37	43,395	36	6.3	79	25	25
4	14	29,577	37	6.3	794	25	25
5	43	39,900	38	4.0	100	25	25
6	6	4,137	28	5.0	316	16	20

(continued)

Table C-10. (continued)

Hydrologic Region	Number of CCW Plants	No. of Measure-ments	No. of Annual Medians	Annual Median TSS (log triangular distribution)			Geometric Mean
				Minimum	Maximum	Weighted Geometric Mean	
7	20	34,494	37	32	1,585	63	100
8	2	46,231	38	50	316	158	126
9	1	3,254	35	13	3,162	32	63
10	20	62,791	38	10	398	126	126
11	8	48,969	38	25	794	200	126
12	6	7,280	35	40	1,995	79	126
13	0	13,974	37	32	79,433	200	398
14	5	26,699	38	16	5,012	158	251
15	4	9,162	37	20	19,953	200	398
16	1	19,965	33	4	2,512	16	25
17	0	173,136	37	2	316	6.0	10
18	2	42,022	37	13	398	63	50
Lakes (national)	56	4,360	99	1	398	25	25

Data source: Legacy STORET database.

For **surface water pH**, the minimum, maximum, and weighted average annual median values were used to specify triangular distributions for each hydrologic region. Table C-11 provides these regional statistics, which were applied to both rivers and lakes.

To prepare the water quality data for the source datafile, the 181 CCW disposal sites were assigned to a hydrogeologic region using a GIS. For each region, 10,000-record TSS and pH data sets were created by sampling the distributions shown in Tables C-10 and C-11. During source data file preparation, TSS data were pulled from the appropriate regional data set sequentially for each iteration at a site.

Table C-11. Regional Surface Water pH Distributions

Hydrologic Region	Number of CCW Plants	No. of Measurements	No. of Annual Median Values	Annual Median pH (triangular distribution)			Average Median pH
				Minimum	Maximum	Weighted Average	
1	0	232,025	38	5.9	7.7	6.5	6.8
2	12	447,166	39	7.2	7.6	7.4	7.4
3	37	1,595,237	39	6.3	7.2	7.0	7.0
4	14	335,261	39	7.6	8.2	8.1	8.0
5	43	684,235	41	3.5	7.5	7.2	7.1
6	6	382,915	39	6.3	7.7	7.2	7.4

(continued)

Table C-11. (continued)

Hydrologic Region	Number of CCW Plants	No. of Measurements	No. of Annual Median Values	Annual Median pH (triangular distribution)			Average Median pH
				Minimum	Maximum	Weighted Average	
7	20	234,589	39	7.6	8.1	7.9	7.8
8	2	171,643	39	6.9	7.8	7.1	7.2
9	1	23,038	38	7.5	8.4	7.9	7.9
10	20	269,570	39	7.6	8.2	8.0	8.0
11	8	311,768	39	7.4	8.1	7.8	7.8
12	6	178,990	39	7.0	7.9	7.8	7.6
13	0	35,355	39	7.0	8.1	8.0	7.9
14	5	77,041	39	7.9	8.3	8.1	8.1
15	4	75,145	38	7.7	8.3	8.0	8.0
16	1	68,581	38	7.5	8.3	8.0	8.0
17	0	293,909	39	6.9	8.0	7.5	7.4
18	2	182,049	38	7.4	8.6	7.8	7.8

Data source: Legacy STORET database.

C.6.4 Distance to Surface Water

Because the CCW plant locations were not accurate in terms of locating the WMUs, a national empirical distribution of distances between the WMU and the nearest downgradient surface waterbodies (discussed in Appendix C, Section C.2.1) was developed using manual measurements on online maps and aerial photographs for a random selection of 30 CCW landfills and 29 CCW surface impoundments. Scaled USGS maps and aerial photographs were obtained from the Terraserver Web site (http://terraserver.usa.com/geographic.aspx) by entering each plant's longitude and latitude. Labels on the maps, features on the photographs, and best professional judgment were used to identify the power plant and the surface impoundment or landfill in question, along with the nearest downgradient waterbody.

The nearest waterbody matching one of the following descriptions was used in the analysis:

- Lakes or rivers beyond the facility boundary
- Streams originating in or passing through the facility boundary and then coursing downstream beyond the property boundary
- Streams with an order of 3 or greater (i.e., fishable waterbodies).

Stream order was determined by tracing the convergence of tributaries with order 1 assigned to the furthest upstream segment indicated on the map (both ephemeral and perennial streams were assigned as order 1). Topography on the map was used to determine if the waterbody was downgradient of the plant. Many CCW WMUs in the sample were located on a large waterbody.

Once the waterbody was identified, the scale provided on the maps and photos was used to measure the horizontal distance between the CCW impoundment or landfill and the waterbody. All assignments and measurements were independently checked for accuracy.

The two distributions (landfills and surface impoundments) were statistically compared using (1) a Wilcoxon Rank Sum Test (to determine whether one distribution is shifted to the right or left of the other distribution) and (2) a Quantile Test (to test for differences, that is, differing numbers of observations) between the two distributions for the values above a given percentile. The results of the Wilcoxon test showed a p value of 0.64, indicating no significant difference in the shape of the distributions. The Quantile Test evaluated every decile from 0.1 to 0.9, with adjustments to the lower percentiles to be estimated for large numbers of ties in the ranks for the lower end of the data. The nonsignificant p values ranged from 0.33 (for 90th percentile) to 0.17 (for the 40th percentile). One significant p value indicating differences between the two distributions occurred at the 17th percentile (p value = 0.066), but the remainder of the tests showed no significant differences. Based on these results, the distributions were judged to be similar and combined to produce the single distribution of 59 values used to produce a single empirical distribution (previously shown in Table C-2) that was applied nationally to both landfills and surface impoundments at the CCW sites.

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Attachment C-1: Soil Data

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
A B Brown	43.9	SCL	6.0	1.2
A B Brown	51.1	SLT	6.5	1.6
A B Brown	5.0	SNL	6.9	1.4
A/C Power- Ace Operations	8.9	SCL	8.9	0.21
A/C Power- Ace Operations	32.0	SLT	8.4	0.46
A/C Power- Ace Operations	59.1	SNL	8.0	0.46
Allen	48.9	SCL	7.1	0.98
Allen	19.2	SLT	6.2	1.1
Allen	32.0	SNL	7.1	1.1
Alma	18.9	SCL	6.6	1.7
Alma	59.4	SLT	6.5	3.4
Alma	21.7	SNL	5.6	0.69
Antelope Valley	8.4	SCL	7.6	3.2
Antelope Valley	68.5	SLT	7.6	1.7
Antelope Valley	23.1	SNL	7.8	2.4
Arkwright	50.7	SCL	5.4	0.5
Arkwright	24.7	SLT	5.6	0.88
Arkwright	24.5	SNL	5.4	0.64
Asheville	6.3	SCL	5.4	0.43
Asheville	77.8	SLT	5.2	0.99
Asheville	15.8	SNL	5.4	1
Baldwin	39.5	SCL	6.2	1.3
Baldwin	58.6	SLT	6.0	1.6
Baldwin	1.9	SNL	6.5	1.4
Barry	35.8	SCL	4.8	3.6
Barry	23.5	SLT	4.8	7
Barry	40.7	SNL	4.8	4.4
Bay Front	11.7	SCL	7.3	4
Bay Front	21.1	SLT	7.1	3.8
Bay Front	67.2	SNL	7.1	1.4
Bay Shore	90.8	SCL	7.1	4.1
Bay Shore	4.3	SLT	7.2	2.6
Bay Shore	4.9	SNL	7.7	9.3
Belews Creek	69.2	SCL	5.2	0.34
Belews Creek	14.0	SLT	5.4	1

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Belews Creek	16.8	SNL	5.2	0.4
Ben French	25.3	SCL	8.0	0.87
Ben French	59.7	SLT	7.7	1.8
Ben French	15.0	SNL	7.1	1.7
Big Cajun 2	66.4	SCL	7.1	1.1
Big Cajun 2	28.4	SLT	6.3	1.2
Big Cajun 2	5.2	SNL	6.0	1.3
Big Sandy	54.8	SCL	5.4	1.6
Big Sandy	41.5	SLT	5.3	1.9
Big Sandy	3.7	SNL	5.1	2.6
Big Stone	7.3	SCL	7.5	5.7
Big Stone	45.0	SLT	7.7	3.1
Big Stone	47.7	SNL	7.5	1.1
Black Dog Steam Plant	8.2	SCL	6.9	4.2
Black Dog Steam Plant	41.4	SLT	6.8	2.5
Black Dog Steam Plant	50.4	SNL	6.9	1.8
Blue Valley	63.8	SCL	6.3	1.5
Blue Valley	31.6	SLT	6.6	2.8
Blue Valley	4.6	SNL	6.5	1.1
Bowen	18.1	SCL	5.0	1.2
Bowen	81.9	SLT	5.0	0.74
Brandon Shores	18.2	SCL	4.5	0.47
Brandon Shores	16.8	SLT	4.6	3.4
Brandon Shores	64.9	SNL	4.8	0.88
Buck	79.1	SCL	5.4	0.39
Buck	18.9	SLT	5.6	1
Buck	2.0	SNL	5.3	0.6
Bull Run	76.7	SCL	5.2	0.92
Bull Run	18.2	SLT	5.6	1.7
Bull Run	5.1	SNL	5.0	0.67
C D McIntosh Jr	6.5	SCL	8.1	2.3
C D McIntosh Jr	93.5	SNL	5.5	1.8
C P Crane	34.1	SCL	4.8	0.52
C P Crane	34.3	SLT	4.7	1
C P Crane	31.6	SNL	4.9	1.1
Cape Fear	67.6	SCL	5.1	0.97
Cape Fear	24.7	SLT	5.4	1.5
Cape Fear	7.7	SNL	5.2	0.66
Carbon	0.4	SCL	6.3	7.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Carbon	95.8	SLT	7.8	3.4
Carbon	3.8	SNL	8.2	1.4
Cardinal	69.1	SCL	5.8	1
Cardinal	30.4	SLT	5.7	1.7
Cardinal	0.5	SNL	6.4	2
Cayuga	32.3	SCL	6.6	1.9
Cayuga	48.7	SLT	7.1	1.4
Cayuga	19.0	SNL	6.8	1.1
Chalk Point	6.9	SCL	4.6	0.58
Chalk Point	16.4	SLT	4.8	8.8
Chalk Point	76.7	SNL	4.6	1.1
Cholla	27.3	SCL	8.4	1.9
Cholla	61.0	SLT	8.1	0.62
Cholla	11.6	SNL	8.3	0.75
Cliffside	66.4	SCL	5.2	0.31
Cliffside	13.6	SLT	5.5	0.77
Cliffside	20.0	SNL	5.2	0.27
Clover	71.0	SCL	5.3	0.71
Clover	23.3	SLT	5.3	1.3
Clover	5.7	SNL	5.1	0.65
Coal Creek	6.1	SCL	6.8	3
Coal Creek	82.7	SLT	7.6	1.7
Coal Creek	11.2	SNL	8.2	2.8
Coleto Creek	12.1	SCL	7.0	1.1
Coleto Creek	86.0	SLT	7.4	0.78
Coleto Creek	1.8	SNL	6.2	0.75
Colstrip	9.0	SCL	8.0	0.79
Colstrip	63.0	SLT	8.2	0.73
Colstrip	27.9	SNL	8.3	0.54
Conemaugh	11.8	SCL	5.0	2.7
Conemaugh	81.4	SLT	4.8	1.3
Conemaugh	6.8	SNL	4.5	1.8
Conesville	44.0	SCL	5.4	2.2
Conesville	45.5	SLT	5.6	1.9
Conesville	10.5	SNL	5.0	2.2
Council Bluffs	43.3	SCL	7.5	1.5
Council Bluffs	47.2	SLT	7.6	1.2
Council Bluffs	9.6	SNL	7.7	0.74
Crawford	48.4	SCL	6.8	1.9

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Crawford	23.6	SLT	6.7	1.4
Crawford	28.0	SNL	6.7	0.82
Crist	18.8	SCL	5.4	4.5
Crist	32.3	SLT	5.3	1.1
Crist	48.8	SNL	5.4	3.3
Cross	3.0	SCL	5.0	1.3
Cross	46.0	SLT	4.6	0.58
Cross	51.0	SNL	4.9	1.2
Cumberland	61.1	SCL	5.3	1.6
Cumberland	34.2	SLT	5.7	0.98
Cumberland	4.8	SNL	5.2	1.3
Dale	91.7	SCL	6.4	1.9
Dale	8.2	SLT	6.4	2
Dale	0.1	SNL	6.7	1.3
Dallman	66.2	SCL	6.4	1.8
Dallman	33.3	SLT	6.7	1.2
Dallman	0.5	SNL	7.0	1.1
Dan E Karn	0.01	SCL	7.0	3
Dan E Karn	53.6	SLT	7.9	4.2
Dan E Karn	46.3	SNL	7.8	5.4
Dan River	73.3	SCL	5.0	0.39
Dan River	12.0	SLT	5.3	1.4
Dan River	14.7	SNL	5.1	0.6
Danskammer	89.8	SLT	5.8	2.9
Danskammer	10.2	SNL	6.9	2.8
Dave Johnston	2.2	SCL	8.9	0.96
Dave Johnston	36.6	SLT	8.2	1.2
Dave Johnston	61.2	SNL	8.2	1.1
Dickerson	6.1	SCL	5.1	0.52
Dickerson	93.9	SLT	5.2	0.68
Dolet Hills	65.7	SCL	4.8	0.97
Dolet Hills	21.6	SLT	5.0	0.77
Dolet Hills	12.7	SNL	5.1	1.1
Duck Creek	65.5	SCL	6.4	0.82
Duck Creek	33.6	SLT	6.5	0.6
Duck Creek	0.9	SNL	7.0	0.98
Dunkirk	8.8	SCL	7.3	5.4
Dunkirk	79.6	SLT	6.9	4.6
Dunkirk	11.6	SNL	6.5	2.7

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
E D Edwards	49.5	SCL	6.4	1.1
E D Edwards	29.8	SLT	6.3	1.2
E D Edwards	20.6	SNL	6.8	1.1
E W Brown	92.9	SCL	6.4	3.7
E W Brown	7.1	SLT	6.6	3.8
Eckert Station	4.8	SCL	7.2	4.5
Eckert Station	82.0	SLT	6.9	1.2
Eckert Station	13.2	SNL	6.7	0.5
Edgewater	58.5	SCL	7.3	3.3
Edgewater	3.7	SLT	7.3	1.2
Edgewater	37.8	SNL	6.8	2.2
Elmer W Stout	29.9	SCL	6.7	1.9
Elmer W Stout	56.7	SLT	7.0	1.2
Elmer W Stout	13.3	SNL	6.8	0.8
F B Culley	45.3	SCL	5.9	0.93
F B Culley	48.9	SLT	6.5	2
F B Culley	5.8	SNL	6.9	1.1
Fayette Power Prj	51.9	SCL	7.7	3.8
Fayette Power Prj	35.7	SLT	7.6	1.2
Fayette Power Prj	12.5	SNL	7.1	1
Flint Creek	62.2	SCL	4.9	0.87
Flint Creek	37.8	SLT	5.3	0.69
Fort Martin	45.9	SCL	5.6	1.2
Fort Martin	54.1	SLT	5.2	1.9
Fort Martin	0.04	SNL	4.6	2.5
Frank E Ratts	30.9	SCL	5.8	1.5
Frank E Ratts	58.0	SLT	6.3	1.1
Frank E Ratts	11.1	SNL	7.0	0.73
G G Allen	85.9	SCL	5.3	0.36
G G Allen	11.9	SLT	5.6	1.1
G G Allen	2.2	SNL	5.2	0.28
Gadsden	45.2	SCL	4.8	0.68
Gadsden	46.4	SLT	5.3	1.3
Gadsden	8.5	SNL	5.1	0.97
Gallatin	56.1	SCL	5.6	0.94
Gallatin	43.9	SLT	5.4	0.94
Gen J M Gavin	35.9	SCL	6.0	1.4
Gen J M Gavin	46.1	SLT	5.6	2.1
Gen J M Gavin	18.0	SNL	5.1	1.3

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Genoa	14.3	SCL	6.1	2.3
Genoa	64.6	SLT	6.6	1.8
Genoa	21.0	SNL	6.1	0.97
Gibson	55.3	SCL	6.6	1.5
Gibson	43.2	SLT	6.4	1.1
Gibson	1.5	SNL	7.3	0.67
Gorgas	17.0	SCL	4.6	0.42
Gorgas	53.0	SLT	5.1	0.77
Gorgas	30.0	SNL	5.2	0.73
Green River	48.4	SCL	5.9	1
Green River	51.6	SLT	6.0	1.4
Greene County	19.5	SCL	5.1	1.8
Greene County	72.6	SLT	5.2	1.4
Greene County	7.9	SNL	4.9	1.6
H B Robinson	0.1	SCL	5.2	0.75
H B Robinson	32.6	SLT	4.8	1
H B Robinson	67.3	SNL	5.3	0.6
Hammond	54.7	SCL	5.1	0.74
Hammond	33.8	SLT	5.3	1.3
Hammond	11.5	SNL	5.0	0.75
Harllee Branch	54.7	SCL	5.3	0.49
Harllee Branch	15.3	SLT	5.6	0.97
Harllee Branch	30.0	SNL	5.3	0.47
Harrison	48.8	SCL	5.6	1
Harrison	51.2	SLT	5.0	2.1
Hatfield's Ferry	39.3	SCL	5.7	1.8
Hatfield's Ferry	60.4	SLT	5.3	1.6
Hatfield's Ferry	0.3	SNL	4.6	2.5
Hennepin	44.6	SCL	6.4	1.5
Hennepin	38.2	SLT	6.7	1.1
Hennepin	17.2	SNL	7.0	1.3
Heskett	39.9	SCL	8.0	2.1
Heskett	44.1	SLT	7.6	2.4
Heskett	16.0	SNL	7.7	1.9
Holcomb	4.4	SLT	7.9	0.67
Holcomb	95.6	SNL	7.3	0.75
Homer City	11.0	SCL	4.9	2.9
Homer City	84.5	SLT	4.8	1.6
Homer City	4.5	SNL	4.5	2.1

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Hoot Lake	3.1	SCL	7.5	5.4
Hoot Lake	38.9	SLT	7.7	2.6
Hoot Lake	58.1	SNL	7.5	1.3
Hugo	55.1	SCL	6.6	1.4
Hugo	35.8	SLT	6.7	1.6
Hugo	9.2	SNL	5.3	0.7
Hunter	90.8	SCL	8.3	0.73
Hunter	3.5	SLT	8.2	2
Hunter	5.7	SNL	8.5	0.75
Huntington	4.5	SCL	8.6	1.5
Huntington	79.5	SLT	8.0	2.4
Huntington	15.9	SNL	8.6	1.3
Intermountain	46.9	SCL	8.6	0.7
Intermountain	8.3	SLT	8.9	0.51
Intermountain	44.8	SNL	8.8	0.44
J H Campbell	5.0	SLT	7.1	1.8
J H Campbell	95.0	SNL	5.9	1.2
J M Stuart	73.5	SCL	6.5	1.6
J M Stuart	24.8	SLT	6.8	2.4
J M Stuart	1.7	SNL	5.5	2
J R Whiting	80.6	SCL	7.1	4.2
J R Whiting	17.1	SLT	7.1	2.1
J R Whiting	2.3	SNL	6.8	2.8
Jack McDonough	58.9	SCL	5.2	0.46
Jack McDonough	7.8	SLT	5.6	1.1
Jack McDonough	33.3	SNL	5.3	0.37
Jack Watson	20.5	SCL	6.7	11
Jack Watson	46.8	SLT	4.8	3
Jack Watson	32.8	SNL	4.9	3.8
James H Miller Jr	17.0	SCL	4.6	0.42
James H Miller Jr	53.0	SLT	5.1	0.77
James H Miller Jr	30.0	SNL	5.2	0.73
Jim Bridger	1.4	SCL	8.7	0.75
Jim Bridger	37.9	SLT	8.6	0.52
Jim Bridger	60.6	SNL	8.2	0.64
John E Amos	35.8	SCL	6.3	1.6
John E Amos	64.2	SLT	5.1	2.2
John Sevier	43.2	SCL	6.2	1.6
John Sevier	56.7	SLT	5.8	1.2

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
John Sevier	0.2	SNL	5.0	0.67
Johnsonville	39.2	SCL	5.1	1.7
Johnsonville	57.3	SLT	5.2	1.3
Johnsonville	3.5	SNL	4.7	1.5
Joliet 29	52.8	SCL	7.1	2.7
Joliet 29	43.5	SLT	7.0	2.1
Joliet 29	3.7	SNL	7.1	1.8
Keystone	7.7	SCL	4.9	2.8
Keystone	90.1	SLT	4.9	1.4
Keystone	2.2	SNL	4.5	2.2
Killen Station	74.3	SCL	6.0	1.9
Killen Station	24.0	SLT	6.3	2.2
Killen Station	1.8	SNL	6.2	1.7
Kingston	66.7	SCL	5.0	1.2
Kingston	21.0	SLT	5.5	1.7
Kingston	12.3	SNL	5.0	0.67
Kraft	57.1	SCL	7.2	11
Kraft	22.8	SLT	5.0	1.3
Kraft	20.1	SNL	5.0	1.4
L V Sutton	18.0	SCL	6.1	3.9
L V Sutton	32.4	SLT	5.0	3.7
L V Sutton	49.6	SNL	5.0	1.6
Lansing	9.0	SCL	5.8	2.6
Lansing	67.7	SLT	6.8	2.1
Lansing	23.3	SNL	6.2	1.4
Laramie R Station	41.1	SLT	8.1	0.87
Laramie R Station	58.9	SNL	7.9	1.2
Lawrence EC	51.5	SCL	6.6	1.9
Lawrence EC	47.7	SLT	6.8	2.9
Lawrence EC	0.8	SNL	7.5	0.75
Lee	16.4	SCL	5.0	1.3
Lee	51.1	SLT	5.0	1.3
Lee	32.5	SNL	5.1	0.96
Leland Olds	13.5	SCL	7.8	2.6
Leland Olds	52.9	SLT	7.6	1.9
Leland Olds	33.6	SNL	7.5	2
Lon Wright	25.7	SCL	7.5	1.5
Lon Wright	8.4	SLT	7.0	2.1
Lon Wright	65.9	SNL	7.8	1.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Louisa	35.5	SCL	6.7	1.8
Louisa	16.6	SLT	6.3	1.5
Louisa	47.9	SNL	6.6	0.96
Marion	10.9	SCL	5.6	0.96
Marion	88.8	SLT	5.2	0.95
Marion	0.3	SNL	6.6	1
Marshall	72.1	SCL	5.2	0.33
Marshall	12.9	SLT	5.5	0.87
Marshall	15.0	SNL	5.2	0.27
Martin Lake	34.3	SCL	4.9	1
Martin Lake	25.1	SLT	5.1	0.8
Martin Lake	40.6	SNL	5.1	0.73
Mayo	71.9	SCL	5.6	0.61
Mayo	27.9	SLT	5.6	1
Mayo	0.2	SNL	5.2	0.76
Meramec	87.9	SCL	6.4	1.3
Meramec	12.1	SLT	6.5	1.3
Merom	30.2	SCL	5.5	0.84
Merom	59.2	SLT	5.8	0.96
Merom	10.6	SNL	6.4	0.77
Miami Fort	69.6	SCL	6.5	1.7
Miami Fort	27.3	SLT	6.8	2
Miami Fort	3.1	SNL	6.7	1.2
Milton R Young	4.6	SCL	7.6	3.1
Milton R Young	92.9	SLT	7.7	1.5
Milton R Young	2.5	SNL	7.5	1.8
Mitchell - PA	19.1	SCL	5.9	2.1
Mitchell - PA	80.9	SLT	5.5	1.4
Mitchell - WV	39.9	SCL	6.0	1.7
Mitchell - WV	59.9	SLT	5.2	2
Mitchell - WV	0.2	SNL	6.0	1.3
Mohave	29.0	SLT	8.1	0.26
Mohave	71.0	SNL	8.1	0.31
Monroe	38.5	SCL	7.0	3
Monroe	49.5	SLT	7.2	3.1
Monroe	12.0	SNL	6.8	3.5
Morgantown	21.7	SCL	4.6	1.2
Morgantown	39.3	SLT	4.7	3.2
Morgantown	39.0	SNL	4.9	1.3

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Mountaineer (1301)	56.1	SCL	6.0	1.6
Mountaineer (1301)	34.2	SLT	5.9	2.2
Mountaineer (1301)	9.8	SNL	4.9	2.5
Mt Storm	4.1	SCL	5.0	2.9
Mt Storm	65.3	SLT	4.7	1.4
Mt Storm	30.6	SNL	4.4	1
Muscatine Plant #1	46.8	SCL	6.6	1.8
Muscatine Plant #1	27.4	SLT	6.4	1.4
Muscatine Plant #1	25.8	SNL	6.6	0.84
Muskogee	30.9	SCL	6.5	1.7
Muskogee	53.1	SLT	6.8	1.1
Muskogee	16.0	SNL	6.7	1
Neal North	36.7	SCL	7.9	1.1
Neal North	46.5	SLT	7.9	0.67
Neal North	16.9	SNL	7.7	0.73
Neal South	34.0	SCL	7.8	1.1
Neal South	50.7	SLT	7.8	0.69
Neal South	15.3	SNL	7.7	0.73
Nebraska City	55.5	SCL	7.4	1.4
Nebraska City	35.5	SLT	7.3	1.7
Nebraska City	9.0	SNL	7.7	0.74
New Castle	5.1	SCL	7.7	0.73
New Castle	81.6	SLT	5.9	2.8
New Castle	13.2	SNL	6.1	1.5
Newton	37.9	SCL	5.5	0.54
Newton	61.3	SLT	5.5	0.53
Newton	0.7	SNL	6.5	0.85
North Omaha	29.0	SCL	7.4	1.5
North Omaha	60.1	SLT	7.7	0.82
North Omaha	11.0	SNL	7.7	0.74
Northeastern	76.9	SCL	6.7	2.1
Northeastern	21.3	SLT	6.3	2.2
Northeastern	1.8	SNL	5.6	2
Nucla	61.2	SLT	7.9	0.98
Nucla	38.8	SNL	8.1	0.55
Oklaunion	92.2	SCL	8.0	1.7
Oklaunion	7.0	SLT	7.9	0.94
Oklaunion	0.7	SNL	7.3	1.5
Paradise	14.8	SCL	5.6	1.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Paradise	85.2	SLT	5.9	1.2
Petersburg	29.7	SCL	5.9	1.5
Petersburg	62.9	SLT	6.3	1.2
Petersburg	7.5	SNL	7.2	0.59
Pleasant Prairie	97.2	SCL	7.1	1.7
Pleasant Prairie	2.8	SNL	7.3	1.5
Port Washington	86.3	SCL	7.3	3.3
Port Washington	7.7	SLT	7.5	0.68
Port Washington	6.1	SNL	7.3	3
Portland	8.7	SCL	5.8	0.58
Portland	90.8	SLT	5.5	1.1
Portland	0.5	SNL	6.0	1.8
Possum Point	6.3	SCL	4.6	0.58
Possum Point	43.0	SLT	4.9	3
Possum Point	50.7	SNL	4.9	0.8
Potomac River	13.3	SCL	4.5	0.56
Potomac River	35.5	SLT	4.9	2.8
Potomac River	51.2	SNL	5.0	1.1
Presque Isle	18.7	SLT	5.2	2.5
Presque Isle	81.3	SNL	5.3	3.1
R Gallagher	40.4	SCL	5.6	1.5
R Gallagher	59.0	SLT	5.9	2.1
R Gallagher	0.5	SNL	6.9	1.4
R M Schahfer	2.1	SCL	7.1	3.8
R M Schahfer	6.5	SLT	6.9	2.9
R M Schahfer	91.4	SNL	6.6	1.5
Reid Gardner	13.3	SCL	8.4	0.29
Reid Gardner	21.6	SLT	8.3	0.58
Reid Gardner	65.1	SNL	8.4	0.34
Richard Gorsuch	69.9	SCL	6.1	1.7
Richard Gorsuch	27.0	SLT	5.9	2.4
Richard Gorsuch	3.0	SNL	5.1	2.6
Riverbend	77.4	SCL	5.3	0.37
Riverbend	20.1	SLT	5.7	1.1
Riverbend	2.5	SNL	5.2	0.45
Rodemacher	42.9	SCL	6.5	0.96
Rodemacher	51.4	SLT	6.5	0.92
Rodemacher	5.7	SNL	5.3	0.85
Roxboro	40.3	SCL	5.5	0.47

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Roxboro	55.7	SLT	6.0	0.79
Roxboro	4.0	SNL	5.5	1.4
Sandow	0.8	SCL	6.9	0.5
Sandow	37.4	SLT	6.3	0.66
Sandow	61.8	SNL	6.3	0.64
Scherer	58.5	SCL	5.3	0.39
Scherer	12.8	SLT	5.5	0.97
Scherer	28.7	SNL	5.3	0.42
Shawnee	9.5	SCL	5.8	1
Shawnee	84.2	SLT	5.6	1.4
Shawnee	6.3	SNL	6.5	1.1
Shawville	5.2	SCL	5.0	3
Shawville	82.6	SLT	4.9	1.1
Shawville	12.2	SNL	4.4	1.2
Sheldon	62.7	SCL	6.8	2.3
Sheldon	33.2	SLT	7.0	1.6
Sheldon	4.1	SNL	6.9	2
South Oak Creek	95.5	SCL	7.1	1.9
South Oak Creek	4.5	SNL	7.3	1.6
Springerville	10.0	SLT	8.1	0.79
Springerville	90.0	SNL	7.9	0.79
St Johns River Power	27.1	SCL	6.9	49
St Johns River Power	0.4	SLT	5.0	1.3
St Johns River Power	72.5	SNL	5.2	1.1
Stanton Energy Ctr	0.8	SCL	7.0	10
Stanton Energy Ctr	2.4	SLT	7.7	1
Stanton Energy Ctr	96.8	SNL	5.3	4.8
Stockton Cogen Company	89.9	SCL	7.6	1.8
Stockton Cogen Company	6.6	SLT	7.5	1.5
Stockton Cogen Company	3.5	SNL	6.8	0.51
Syl Laskin	8.5	SCL	6.5	3.2
Syl Laskin	4.6	SLT	6.3	6.3
Syl Laskin	86.9	SNL	5.8	3.1
Tecumseh EC	55.2	SCL	6.6	2
Tecumseh EC	41.9	SLT	6.9	2.6
Tecumseh EC	2.9	SNL	7.6	0.62
Texas-New Mexico	4.4	SCL	7.0	0.61
Texas-New Mexico	43.5	SLT	6.3	0.67
Texas-New Mexico	52.1	SNL	6.0	0.77

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Titus	31.8	SCL	6.0	0.76
Titus	63.6	SLT	5.6	1.4
Titus	4.6	SNL	5.0	0.98
Trimble County	57.3	SCL	6.3	2
Trimble County	41.9	SLT	6.5	1.9
Trimble County	0.8	SNL	5.9	1.7
Tyrone	92.1	SCL	6.3	3.7
Tyrone	7.9	SLT	6.6	3.9
Valley	98.5	SCL	6.9	1.2
Valley	0.2	SLT	7.5	0.45
Valley	1.3	SNL	7.4	1.3
Vermilion	82.5	SCL	6.9	1.3
Vermilion	16.6	SLT	7.0	1.2
Vermilion	0.8	SNL	7.2	1.1
Victor J Daniel Jr	46.2	SCL	4.6	2.2
Victor J Daniel Jr	27.7	SLT	4.7	2.3
Victor J Daniel Jr	26.1	SNL	4.7	16
W A Parish	95.8	SCL	7.4	1.4
W A Parish	4.2	SLT	7.9	0.74
W H Weatherspoon	7.4	SCL	5.5	1.9
W H Weatherspoon	50.4	SLT	4.7	2.2
W H Weatherspoon	42.2	SNL	4.8	1.3
W S Lee	68.0	SCL	5.3	0.48
W S Lee	9.0	SLT	5.7	1
W S Lee	23.0	SNL	5.3	0.41
Wabash River	22.0	SCL	6.4	1.6
Wabash River	48.5	SLT	6.9	1.2
Wabash River	29.5	SNL	6.7	1.2
Walter C Beckjord	71.6	SCL	6.3	1.4
Walter C Beckjord	26.5	SLT	6.7	2
Walter C Beckjord	1.9	SNL	6.6	1.1
Wansley	46.3	SCL	5.2	0.52
Wansley	18.1	SLT	5.6	1.2
Wansley	35.5	SNL	5.4	0.5
Warrick	45.8	SCL	6.0	0.95
Warrick	48.6	SLT	6.5	1.9
Warrick	5.6	SNL	7.0	1.1
Waukegan	43.9	SCL	6.6	1
Waukegan	18.1	SLT	6.6	1.4

(continued)

Soil Data (continued)

Plant	Percent Composition	Megatexture Code	Average pH	Average % Organic Material
Waukegan	38.0	SNL	6.7	0.8
Weston	33.5	SLT	5.6	1.7
Weston	66.5	SNL	6.0	1.4
Widows Creek	64.5	SCL	5.3	0.88
Widows Creek	20.0	SLT	5.2	1.4
Widows Creek	15.5	SNL	5.4	1.2
Will County	40.0	SCL	6.8	1.8
Will County	52.7	SLT	7.0	0.96
Will County	7.2	SNL	7.1	0.98
Wyodak	1.3	SCL	8.1	0.38
Wyodak	40.2	SLT	7.9	1.1
Wyodak	58.5	SNL	7.9	0.93
Yates	47.8	SCL	5.2	0.48
Yates	17.7	SLT	5.6	1.2
Yates	34.5	SNL	5.3	0.48

Attachment C-2: Hydrogeologic Environment

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Big Cajun 2	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting (100% alluvium); soils have significant fines (SCL+SLT = 95%)
A B Brown	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 95%)
A/C Power-Ace Operations	2C	Alluvial Fans	5	Alluvial Basins Valleys and Fans	100	Based on surficial geology; consistent with alluvial fan setting
Allen	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on aquifer coverages, surficial geology; Heath (1985) and soils indicate overbank deposits
Alma	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on SNL/SCL soils; setting based on productive aquifers and surficial geology
Alma	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on SNL/SCL soils; setting based on productive aquifers and surficial geology
Antelope Valley	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on principal aquifer and surficial geology coverages
Arkwright	8D	Regolith	1	Metamorphic and Igneous	100	Most common Piedmont setting (residuum)
Asheville	8B	Alluvial Mountain Valleys	5	Alluvial Basins Valleys and Fans	100	Appropriate for alluvial blue ridge valley (colluvium)
Baldwin	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology (74% Floodplain and alluvium gravel terraces)
Baldwin	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	30	Percentage based on surficial geology (74% Floodplain and alluvium gravel terraces)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Barry	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting, significant fine grained soils = overbank deposits
Bay Front	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	70	Percentage based on productive aquifers
Bay Front	7D	Buried Valley	4	Sand and Gravel	30	Percentage based on productive aquifers
Bay Shore	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Closest setting considering carbonate aquifers, high SCL soils, and lake deposits surficial geology
Belews Creek	6H	Triassic Basins	2	Bedded Sedimentary Rock	50	Sources somewhat dissimilar; fraction based on surficial geology; Triassic basin
Belews Creek	8D	Regolith	1	Metamorphic and Igneous	50	Sources somewhat dissimilar; fraction based on surficial geology
Ben French	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	60	Percentage, thin soils based on surficial geology
Ben French	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; significant fine soils (25% SCL)
Big Sandy	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	50	Percentage based on surficial geology; thin soils inferred from colluvium
Big Sandy	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on surficial geology; soils have significant fines (SCL+SLT = 95%)
Big Stone	7Ba	Outwash	8	Outwash	100	Based on surficial geology
Black Dog Steam Plant	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	100	Based on surficial geology, aquifer coverages
Blue Valley	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	80	Percentage based on Heath (1985), productive aquifers

(continued)

Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Blue Valley	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	20	Percentage based on Heath (1985), productive aquifers
Bowen	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Based on aquifers, surficial residuum (massive red clay); metamorphic surficial geology not consistent with Valley and Ridge
Brandon Shores	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Assigned based on location and aquifer and surficial geology coverages; Heath region incorrect (it's Atlantic Coastal Plain, not Piedmont)
Buck	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	100	Based on productive aquifer & Heath region coverages
Bull Run	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	60	Percentage based on surficial geology
Bull Run	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; high SCL (77%) = overbank deposits
C D McIntosh Jr	11A	Solution Limestone and Shallow Surficial Aquifers	12	Solution Limestone	100	Based on both aquifer coverages
C P Crane	10Aa	Regional Aquifers	4	Sand and Gravel	50	Appears to be on border between Piedmont and Coastal Plain
C P Crane	8D	Regolith	1	Metamorphic and Igneous	50	Appears to be on border between Piedmont and Coastal Plain
Cape Fear	6H	Triassic Basins	2	Bedded Sedimentary Rock	20	Percentage based on productive aquifer & Heath region coverages; Triassic basin
Cape Fear	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on productive aquifer & Heath region coverages
Carbon	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverages

(continued)

Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Cardinal	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	30	Percentage based on surficial geology; soils with low (<1%) SNL
Cardinal	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology; soils with low (<1%) SNL
Cayuga	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer overlaid by alluvial deposits
Chalk Point	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Predominant setting
Cholla	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
Cholla	4C	River Alluvium	7	River Valleys and Floodplains without Overbank Deposits	80	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
Cliffside	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Clover	6H	Triassic Basins	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; Triassic Basin from Heath (1985) and principal aquifer coverage
Clover	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology
Coal Creek	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on principal aquifer and surficial geology coverages
Coleto Creek	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages
Colstrip	6da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Based on all coverages

(continued)

Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Conemaugh	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium
Conesville	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; soils with low (10%) SNL
Conesville	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; soils with low (10%) SNL
Council Bluffs	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on productive aquifers
Crawford	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on predominant surficial geology (98% Floodplain and alluvium gravel terraces), productive aquifer coverage
Crist	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Assigned based on predominant surficial geology (96% Floodplain and alluvium gravel terraces), coarse-grained soil (49% SNL)
Cross	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifers, surficial geology, soils, Heath (1985)
Cumberland	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surface geology; high (61%) SCL = overbank deposits
Dale	6E	Solution Limestone	12	Solution Limestone	20	Percentage based on surficial geology; setting from principal aquifers (carbonate)
Dale	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; soils have significant fines (SNL = 0.1%)
Dallman	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on soils, surficial geology, principal aquifer
Dan E Karn	7F	Glacial Lake Deposits	4	Sand and Gravel	100	Based on surficial geology, soils

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Dan River	6H	Triassic Basins	2	Bedded Sedimentary Rock	100	Based on surfucial geology, principal aquifers; Triassic basin
Danskammer	7D	Buried Valley	4	Sand and Gravel	100	Based on predominant Heath region, productive aquifers; little coarse-grained soils
Dave Johnston	4C	River Alluvium	7	River Valleys and Floodplains without Overbank Deposits	100	Based on aquifer and surficial geology coverages, Heath (1985)
Dickerson	8D	Regolith	1	Metamorphic and Igneous	100	Predominant setting
Dolet Hills	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Predominant shallow unconsolidated aquifer system
Duck Creek	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on predominant surficial geology (100% Floodplain and alluvium gravel terraces), Heath Alluvial Valley Region
Dunkirk	7H	Beaches, Beach Ridges and Sand Dunes	11	Coastal Beaches	100	Based on location, surficial geology
E D Edwards	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	20	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
E D Edwards	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology (83% Floodplain and alluvium gravel terraces)
E W Brown	6E	Solution Limestone	12	Solution Limestone	20	Percentage based on surficial geology (76% alluvium, 23% clay); soils have significant fine-grained (0% SNL)
E W Brown	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology (76% alluvium, 23% clay); soils have significant fine-grained (0% SNL)
Eckert Station	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	30	Percentage based on productive aquifer coverage, Heath regions

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Eckert Station	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on productive aquifer coverage, Heath regions
Edgewater	7Bc	Outwash Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and surficial geology coverages
Elmer W Stout	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer overlaid by alluvial deposits
F B Culley	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 94%)
Fayette Power Prj	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages
Flint Creek	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Ozark plateau; Heath (1985) indicates dolomite, sandy dolomite, sandstone, with no indication of solutioning. Surficial geology (cherty red clay) noted as thick regolith in Aller et al. (1987)
Fort Martin	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surficial geology; low SNL (< 1%) = overbank deposits
Frank E Ratts	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in alluvial valley region (99%)
G G Allen	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Gadsden	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	30	Percentage assigned based on productive aquifer coverage
Gadsden	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage assigned based on productive aquifer coverage; soils have significant fines (SCL+SLT > 25%)
Gallatin	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surface geology; high (56%) SCL = overbank deposits

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Gen J M Gavin	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on productive aquifers, surficial geology
Genoa	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on SNL/SCL soils; setting based on surficial geology and productive aquifers
Genoa	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on SNL/SCL soils; setting based on surficial geology and productive aquifers
Gibson	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 99%)
Gorgas	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	30	Percentage based on surficial geology; alluvial setting with coarser soils (= no overbank deposits)
Gorgas	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on surficial geology; alluvial setting with coarser soils (= no overbank deposits)
Green River	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting (>85% alluvium); soils have significant fines (SNL = 0%)
Greene County	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 90%)
Greene County	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 90%)
H B Robinson	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifers, surficial geology, soils, Heath (1985); Heath region coverage incorrect (Coastal Plain, not Piedmont)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Hammond	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Based on aquifers, surficial residuum (massive red clay)
Harllee Branch	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on predominant surficial geology (99% floodplain and alluvium gravel terraces)
Harrison	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; thin soils inferred from surficial geology
Harrison	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; 0%SNL = overbank deposits
Hatfield's Ferry	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; thin regolith inferred from colluvium
Hatfield's Ferry	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; soils < 1% SNL
Hennepin	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	30	Percentage to capture uncertainty in soils, surficial geology, principal aquifer
Hennepin	7Bb	Outwash Over Bedded Sedimentary Rock	2	Bedded Sedimentary Rock	30	Percentage to capture uncertainty in soils, surficial geology, principal aquifer
Hennepin	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage to capture uncertainty in soils, surficial geology, principal aquifer
Heskett	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvium surficial geology(96%); mixed soils
Holcomb	5Gb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Alluvial valley with very coarse soils
Homer City	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Hoot Lake	9E	Outwash	8	Outwash	100	Based on productive aquifer, soils, surficial geology
Hugo	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; soil/regolith thickness inferred from Heath (1985)
Hugo	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; fine soils with about 10% SNL
Hunter	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverages
Huntington	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverages
Intermountain	2E	Playa Lakes	5	Alluvial Basins Valleys and Fans	100	Setting based on surficial geology coverage, Heath (1985)
J H Campbell	7F	Glacial Lake Deposits	4	Sand and Gravel	100	Based on surficial geology, soils
J M Stuart	6E	Solution Limestone	12	Solution Limestone	50	Percentage based on surficial geology; low (< 2%) SNL
J M Stuart	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on surficial geology; low (< 2%) SNL
J R Whiting	7F	Glacial Lake Deposits	4	Sand and Gravel	100	Based on surficial geology
Jack McDonough	8C	Mountain Flanks	2	Bedded Sedimentary Rock	100	Assigned based on predominant surficial geology (94% stony colluvium on metamorphic rocks; less silt and clay than in colluvium over limestone)
Jack Watson	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Based on all coverages
James H Miller Jr	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 25%)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
James H Miller Jr	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 25%)
Jim Bridger	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Based on aquifer and surficial geology coverages, Heath (1985)
John E Amos	6da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology; thin soils inferred from surficial geology
John E Amos	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; 0%SNL = overbank deposits
John Sevier	6E	Solution Limestone	12	Solution Limestone	50	Percentage based on surface geology; setting based on surface geology and aquifer type, with possibility of solution limestone from Heath (1985)
John Sevier	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage, setting based on surface geology; low (<1%) SNL = overbank deposits
Johnsonville	6E	Solution Limestone	12	Solution Limestone	30	Percentage based on surface geology; setting based on aquifer coverages, Heath (1985); placed in Nonglaciated Central region based on aquifer coverages and Heath (1985)
Johnsonville	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage, setting based on surface geology; low (3%) SNL = overbank deposits; placed in Nonglaciated Central region based on aquifer coverages and Heath (1985)
Joliet 29	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on aquifers, soils; soils don't suggest outwash like surficial geology does
Keystone	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium
Killen Station	6E	Solution Limestone	12	Solution Limestone	30	Percentage based on surficial geology; low (< 2%) SNL

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Killen Station	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology; low (< 2%) SNL
Kingston	6E	Solution Limestone	12	Solution Limestone	20	Percentage based on surface geology; setting based on surface geology and aquifer type, with possibility of solution limestone from Heath (1985)
Kingston	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage, setting based on surface geology; high (67 %) SCL = overbank deposits
Kraft	11A	Solution Limestone and Shallow Surficial Aquifers	12	Solution Limestone	100	Only possible assignment; predominant alluvium (84%) not well represented
L V Sutton	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	20	Percentage based on surficial geology; sandy soils
L V Sutton	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	80	Percentage based on surficial geology; sandy soils
Lansing	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology, productive aquifers; loess = thin soils
Lansing	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	60	Percentage based on surficial geology, productive aquifers; coarse-grained soils
Laramie R Station	6Fb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Based on aquifer and surficial geology coverages, Heath (1985)
Lawrence EC	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial valley with low coarse soils (<1% SNL)
Lee	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology; sandy soils
Lee	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on surficial geology; sandy soils

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Leland Olds	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on surficial geology; assumed coarse soils
Leland Olds	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	50	Percentage based on surficial geology; assumed coarse soils
Lon Wright	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	30	Alluvial based on predominant Heath, productive aquifer; percentage based on soil textures
Lon Wright	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Alluvial based on predominant Heath, productive aquifer; percentage based on soil textures
Louisa	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Alluvial Valley; significant coarse-grained deposits
Louisa	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Alluvial Valley; significant coarse-grained deposits
Marion	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Assigned to Glaciated Central region based on surficial geology (pre-Wisconsin drift)
Marshall	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Martin Lake	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages
Mayo	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Meramec	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Based on surficial, predominant Heath
Merom	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer overlaid by alluvial deposits
Miami Fort	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on productive aquifers, surficial geology and soil (3% SNL)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Milton R Young	7G	Thin Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on principal aquifer and surficial geology coverages
Mitchell	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	60	Percentage based on surficial geology; thin regolith inferred from colluvium
Mitchell	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; soils 0 % SNL
Mitchell	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surficial geology; low SNL (< 1%) = overbank deposits
Mohave	2Ha	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on predominant surficial geology, Heath (1985)
Monroe	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Based on Heath region, productive aquifers, soils
Morgantown	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Assigned based on location and aquifer and surficial geology coverages; Heath region incorrect (it's Atlantic Coastal Plain, not Piedmont)
Mountaineer (1301)	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Setting based on surficial geology; low SNL (10%) = overbank deposits
Mt Storm	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on surficial geology, aquifer coverages; thin soils inferred from surficial geology
Muscatine Plant #1	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Alluvial Valley; significant coarse-grained deposits
Muscatine Plant #1	7Eb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Alluvial Valley; significant coarse-grained deposits
Muskogee	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Surficial geology indicates alluvium/colluvium; Heath (1985) indicates fine soils over sands and gravels

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Neal North	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial Valley setting
Neal South	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial Valley setting
Nebraska City	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial based on predominant Heath, productive aquifer, soil textures
New Castle	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	20	Percentage and setting based on Heath region & surficial geology; thin regolith inferred from colluvium
New Castle	7D	Buried Valley	4	Sand and Gravel	80	Percentage and setting based on Heath region & book
Newton	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on soils, surficial geology, aquifer coverages
North Omaha	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial based on predominant Heath, productive aquifer; soil texture (28% SCL, 10% SNL) = overbank deposits
Northeastern	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	40	Percentage based on surficial geology, which indicates thin residual soils
Northeastern	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology; soils < 2% SNL
Nucla	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Based on surficial geology, aquifer coverages
Oklaunion	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on surficial geology; thin soil inferred
Paradise	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting (93% alluvium); soils have significant fines (SNL = 0%)
Petersburg	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in alluvial valley region (similar to 1043)

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Pleasant Prairie	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Port Washington	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Portland	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and surficial geology coverage
Possum Point	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Based on productive aquifer coverage; Heath region incorrect
Potomac River	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	50	Percentage based on surficial geology coverage; Heath region incorrect
Potomac River	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	50	Percentage based on surficial geology coverage; sandy soils (51% SNL) = no overbank deposits; Heath region incorrect
Presque Isle	9F	Moraine	4	Sand and Gravel	100	Based on surficial geology, Heath region, soils
R Gallagher	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 99%)
R M Schahfer	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in alluvial valley region
Reid Gardner	2C	Alluvial Fans	5	Alluvial Basins Valleys and Fans	100	Based on surficial geology; consistent with productive aquifers
Richard Gorsuch	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Assigned based on productive aquifers, surficial geology and soil (3% SNL)
Riverbend	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology
Rodemacher	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	50	Setting percentage determined from Heath, productive aquifer, and surficial geology coverages

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Rodemacher	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Setting percentage determined from Heath, productive aquifer, and surficial geology coverages
Roxboro	8D	Regolith	1	Metamorphic and Igneous	100	Based on surficial geology, productive aquifers
Sandow	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Setting based on aquifer and surficial geology coverages; Heath region coverage is incorrect (based on Heath [1985] and aquifer coverages)
Scherer	8D	Regolith	1	Metamorphic and Igneous	100	Most common Piedmont setting (residuum)
Shawnee	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	100	Predominant alluvial setting (100% alluvium); soils have low fines (SCL = 9%)
Shawville	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Setting based on aquifer coverages & Heath (1985); thin regolith inferred from colluvium
Sheldon	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	30	Percentage based on productive aquifer coverage; buried valley indicated by Heath (1985)
Sheldon	7D	Buried Valley	4	Sand and Gravel	70	Percentage based on productive aquifer coverage; buried valley indicated by Heath (1985)
South Oak Creek	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Springerville	4B	Consolidated Sedimentary Rock	2	Bedded Sedimentary Rock	100	Assigned based on productive aquifers (consolidated sandstone)
St Johns River Power	11B	Coastal Deposits	4	Sand and Gravel	100	Based on sea island surficial geology
Stanton Energy Ctr	11A	Solution Limestone and Shallow Surficial Aquifers	12	Solution Limestone	100	Based on both aquifer coverages

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Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Stockton Cogen Company	2C	Alluvial Fans	5	Alluvial Basins Valleys and Fans	50	Percentage based on surficial geology; Central Valley soils show significant fines
Stockton Cogen Company	2Ha	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	50	Percentage based on surficial geology; Central Valley soils show significant fines
Syl Laskin	9E	Outwash	8	Outwash	60	Percentage based on surficial geology
Syl Laskin	9Ga	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology
Tecumseh EC	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Alluvial valley with low coarse soils (<3% SNL)
Texas-New Mexico	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	100	Based on productive aquifers, Heath (1985) (Heath region coverage is incorrect)
Titus	6Db	Alternating Sandstone, Limestone and Shale - Deep Regolith	2	Bedded Sedimentary Rock	100	Setting based on aquifer and surficial geology coverage; deep regolith inferred from red, massive clay
Trimble County	6E	Solution Limestone	12	Solution Limestone	40	Heath incorrect; Percentage based on surficial geology (56% alluvium, 44% clay); soils have significant fine-grained (1% SNL)
Trimble County	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Heath incorrect; Percentage based on surficial geology (56% alluvium, 44% clay); soils have significant fine-grained (1% SNL)
Tyrone	6E	Solution Limestone	12	Solution Limestone	100	Based on principal aquifer coverage
Valley	7Ac	Glacial Till Over Solution Limestone	12	Solution Limestone	100	Setting based on aquifer and soil coverages (high SCL soils)
Vermilion	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	100	Based on aquifers, soils; soils don't suggest outwash like surficial geology does
Victor J Daniel Jr	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	60	Percentage based on surficial geology

(continued)

Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Victor J Daniel Jr	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology, soils
W A Parish	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology and productive aquifer coverages
W A Parish	10Ba	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology and productive aquifer coverages; high SCL (96%) = overbank deposits
W H Weatherspoon	10Ab	Unconsolidated and Semi-Consolidated Shallow Surficial Aquifer	10	Unconsolidated and Semiconsolidated Shallow Aquifers	30	Percentage based on surficial geology; sandy soils
W H Weatherspoon	10Bb	River Alluvium Without Overbank Deposits	7	River Valleys and Floodplains without Overbank Deposits	70	Percentage based on surficial geology; sandy soils
W S Lee	8D	Regolith	1	Metamorphic and Igneous	100	Setting based on aquifers, surficial geology, soils, Heath (1985)
Wabash River	7D	Buried Valley	4	Sand and Gravel	100	Glaciofluvial aquifer in Alluvial Valley region
Walter C Beckjord	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	60	Percentage based on surficial geology; placed in glaciated central based on Heath (1985); soils 2% SNL
Walter C Beckjord	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	40	Percentage based on surficial geology; placed in glaciated central based on Heath (1985); soils 2% SNL
Wansley	8C	Mountain Flanks	2	Bedded Sedimentary Rock	30	Percentage based on surficial geology
Wansley	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	70	Percentage based on surficial geology
Warrick	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	100	Predominant alluvial setting; soils have significant fines (SCL+SLT = 94%)
Waukegan	7Bc	Outwash Over Solution Limestone	12	Solution Limestone	100	Based on soils, surficial geology, aquifer coverages

(continued)

Hydrogeologic Environment (continued)

Plant	Hydrogeologic Setting		Hydrogeologic Environment		Percentage	Comment
	Code	Description	Code	Description		
Weston	9E	Outwash	8	Outwash	100	Setting based on productive aquifer, surficial geology coverages
Widows Creek	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	20	Percentage based on surficial geology; thin soils inferred from colluvium
Widows Creek	6Fa	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	80	Percentage based on surficial geology; soils have significant fines (SCL+SLT > 25%)
Will County	7Aa	Glacial Till Over Bedded Sedimentary Rock	3	Till Over Sedimentary Rock	40	Percentage based on surficial geology (65% Floodplain and alluvium gravel terraces)
Will County	7Ea	River Alluvium With Overbank Deposits	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage based on surficial geology (65% Floodplain and alluvium gravel terraces)
Wyodak	6Da	Alternating Sandstone, Limestone and Shale - Thin Soil	2	Bedded Sedimentary Rock	100	Based on aquifer and surficial geology coverages, Heath (1985)
Yates	8D	Regolith	1	Metamorphic and Igneous	40	Percentage assigned based on surficial geology (59% alluvium/colluvium, 42% residuum)
Yates	8E	River Alluvium	6	River Valleys and Floodplains with Overbank Deposit	60	Percentage assigned based on surficial geology (59% alluvium/colluvium, 42% residuum)

SCL = silty clay loam; SNL = sandy loam; SLT = silt loam.

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Heath, R.C. 1985. *National Water Summary 1984. State Summaries of Groundwater Resources*. Water-Supply Paper 2275. U.S. Geological Survey, Washington, DC.

Attachment C-3: Climate Center Assignments

Plant	Climate Center	Explanation If Not Closest Climate Center
A B Brown	Indianapolis, IN	Closest Met Station (Nashville) receives much more precipitation (12.26” out of range) than the site location. Used second closest because only slightly below (1.3) expected precipitation range for plant.
A/C Power- Ace Operations	Las Vegas, NV	
Allen	Little Rock, AR	
Alma	Madison, WI	Closest Met Station (St. Cloud) receives less rain than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Antelope Valley	Bismarck, ND	
Arkwright	Watkinsville, GA	Closest Met Station (Atlanta) receives 6.96” more precipitation than plant location. Used second closest Met Station because 5-year averages are only slightly above (0.2) expected precipitation range for the plant.
Asheville	Knoxville, TN	
Baldwin	East St. Louis, IL	
Barry	Tallahassee, FL	Closest Met Station (New Orleans) receives much more precipitation (5.06” out of range) than the site location. Used second closest because only slightly above (3.4) expected precipitation range for plant.
Bay Front	Madison, WI	
Bay Shore	Put-in-Bay, OH	
Belews Creek	Greensboro, NC	
Ben French	Rapid City, SD	
Big Cajun 2	Lake Charles, LA	Closest Met Station (New Orleans) receives much more precipitation (5.06” out of range) than the site location. Used second closest because only slightly below (2.77) expected precipitation range for plant.
Big Sandy	Cincinnati, OH	Closest Met Station (Lexington) receives much more precipitation (8.35” out of range) than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Big Stone	St. Cloud, MN	

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Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Black Dog Steam Plant	Madison, WI	Closest Met Station (St Cloud) is dryer (<27.5”) than the 28-33” that the site receives. Madison fits in precipitation range (32.5”) and is second closest.
Blue Valley	Topeka, KS	
Bowen	Atlanta, GA	
Brandon Shores	Seabrook, NJ	
Buck	Greensboro, NC	
Bull Run	Knoxville, TN	
C D McIntosh Jr	Orlando, FL	Closest Met Station (Tampa) receives less precipitation (5.31” out of range) than site location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
C P Crane	Seabrook, NJ	
Cape Fear	Greensboro, NC	
Carbon	Salt Lake City, UT	
Cardinal	Pittsburgh, PA	
Cayuga	Indianapolis, IN	
Chalk Point	Seabrook, NJ	
Cholla	Phoenix, AZ	Closest Met Station (Flagstaff) receives much more precipitation (13.92” out of range) than plant location. Used second closest Met Station because 5-year averages were close (.31 higher) than the expected precipitation range for the plant.
Cliffside	Greensboro, NC	
Clover	Lynchburg, VA	
Coal Creek	Bismarck, ND	
Coleto Creek	San Antonio, TX	
Colstrip	Glasgow, MT	
Conemaugh	Pittsburgh, PA	
Conesville	Columbus, OH	
Council Bluffs	North Omaha, NE	
Crawford	East St. Louis, IL	
Crist	Tallahassee, FL	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Cross	Charleston, SC	
Cumberland	Nashville, TN	
Dale	Lexington, KY	
Dallman	East St. Louis, IL	
Dan E Karn	East Lansing, MI	
Dan River	Greensboro, NC	
Danskammer	Bridgeport, CT	
Dave Johnston	Cheyenne, WY	
Dickerson	Seabrook, NJ	
Dolet Hills	Shreveport, LA	
Duck Creek	East St. Louis, IL	
Dunkirk	Ithaca, NY	
E D Edwards	Chicago, IL	
E W Brown	Lexington, KY	
Eckert Station	East Lansing, MI	
Edgewater	Madison, WI	
Elmer W Stout	Indianapolis, IN	
F B Culley	Indianapolis, IN	Closest Met Station (Nashville) receives much more precipitation (12.26” out of range) than plant location. Used second closest Met Station because 5-year & 30-year averages fell within expected precipitation range for the plant.
Fayette Power Prj	San Antonio, TX	
Flint Creek	Columbia, MO	Used http://www.weather.com and Envirofacts to determine that avg. precipitation for site was ~47”. The closest Met Station (Tulsa) receives much less (~17”) precipitation per year. Used second closest station.
Fort Martin	Pittsburgh, PA	
Frank E Ratts	Indianapolis, IN	
G G Allen	Greensboro, NC	
Gadsden	Atlanta, GA	

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Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Gallatin	Nashville, TN	
Gen J M Gavin	Cincinnati, OH	Closest Met Station (Columbus) receives less rain than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com
Genoa	Madison, WI	
Gibson	Indianapolis, IN	
Gorgas	Atlanta, GA	
Green River	Indianapolis, IN	Closest Met Station (Nashville) receives much more precipitation (12.26” out of range) than plant location. Used third closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Greene County	Atlanta, GA	
H B Robinson	Charleston, SC	
Hammond	Atlanta, GA	
Harllee Branch	Watkinsville, GA	
Harrison	Pittsburgh, PA	
Hatfield’s Ferry	Pittsburgh, PA	
Hennepin	Chicago, IL	
Heskett	Bismarck, ND	
Holcomb	Dodge City, KS	
Homer City	Pittsburgh, PA	
Hoot Lake	St. Cloud, MN	
Hugo	Shreveport, LA	Closest Met Station (Dallas) receives less precipitation (6.45” out of range) than plant location. Used second closest because only slightly above (2.07) expected precipitation range for plant.
Hunter	Grand Junction, CO	Closest Met Station (Salt Lake City) receives 8.6” more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Huntington	Cedar City, UT	Two closest Met Stations are out of range. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Intermountain	Ely, NV	Closest Met Station (Salt Lake City) receives 6.1” more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
J H Campbell	East Lansing, MI	

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Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
J M Stuart	Cincinnati, OH	
J R Whiting	Put-in-Bay, OH	
Jack McDonough	Atlanta, GA	
Jack Watson	Tallahassee, FL	Closest Met Station (New Orleans) receives much more precipitation (5.06" out of range) than the site location. http://www.weather.com predicted average precipitation at plant location to be 65.2. Used third closest because its average was closest.
James H Miller Jr	Atlanta, GA	
Jim Bridger	Lander, WY	
John E Amos	Cincinnati, OH	The two closest Met Stations are out of the site's precipitation range. Used third closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com average.
John Sevier	Knoxville, TN	
Johnsonville	Nashville, TN	
Joliet 29	Chicago, IL	
Keystone	Pittsburgh, PA	
Killen Station	Cincinnati, OH	
Kingston	Knoxville, TN	
Kraft	Charleston, SC	
L V Sutton	Charleston, SC	
Lansing	Madison, WI	
Laramie R Station	Cheyenne, WY	
Lawrence EC	Topeka, KS	
Lee	Greensboro, NC	
Leland Olds	Bismarck, ND	
Lon Wright	North Omaha, NE	
Louisa	Des Moines, IA	
Marion	East St. Louis, IL	
Marshall	Greensboro, NC	

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Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Martin Lake	Shreveport, LA	
Mayo	Lynchburg, VA	
Meramec	East St. Louis, IL	
Merom	Indianapolis, IN	
Miami Fort	Cincinnati, OH	
Milton R Young	Bismarck, ND	
Mitchell - PA	Pittsburgh, PA	
Mitchell - WV	Pittsburgh, PA	
Mohave	Las Vegas, NV	
Monroe	Put-in-Bay, OH	
Morgantown	Norfolk, VA	
Mountaineer (1301)	Cincinnati, OH	Closest Met Station (Columbus) receives more rain than plant location. Although second closest site also falls within range, used third closest Met Station because site geography was similar and the station's 5-year averages fell within expected precipitation range for the plant.
Mt Storm	Pittsburgh, PA	
Muscatine Plant #1	Des Moines, IA	
Muskogee	Tulsa, OK	
Neal North	North Omaha, NE	
Neal South	North Omaha, NE	
Nebraska City	North Omaha, NE	
New Castle	Pittsburgh, PA	
Newton	Indianapolis, IN	Closest Met Station (East St. Louis) receives less rain than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com
North Omaha	North Omaha, NE	
Northeastern	Tulsa, OK	
Nucla	Grand Junction, CO	

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Oklaunion	Oklahoma City, OK	
Paradise	Cincinnati, OH	Closest Met Station (Nashville) receives much more precipitation (12.26” out of range) than plant location. Used third closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Petersburg	Indianapolis, IN	
Pleasant Prairie	Chicago, IL	
Port Washington	Madison, WI	
Portland	Philadelphia, PA	
Possum Point	Norfolk, VA	
Potomac River	Seabrook, NJ	
Presque Isle	Sault Ste. Marie, MI	
R Gallagher	Cincinnati, OH	Closest Met Station (Lexington) receives much more precipitation (8.35” out of range) than plant location. Used second closest Met Station because 5-year & 30-year averages fell within expected precipitation range for the plant.
R M Schahfer	Chicago, IL	
Reid Gardner	Las Vegas, NV	
Richard Gorsuch	Columbus, OH	
Riverbend	Greensboro, NC	
Rodemacher	Lake Charles, LA	
Roxboro	Greensboro, NC	
Sandow	San Antonio, TX	
Scherer	Watkinsville, GA	Closest Met Station (Atlanta) receives 6.96” more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Shawnee	East St. Louis, IL	
Shawville	Pittsburgh, PA	
Sheldon	North Omaha, NE	

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Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
South Oak Creek	Chicago, IL	
Springerville	Albuquerque, NM	Closest Met Station (Flagstaff) receives much more precipitation (8.92” out of range) than plant location. Used second closest Met Station because 5-year averages were within the expected precipitation range for the plant.
St Johns River Power	Jacksonville, FL	
Stanton Energy Ctr	Orlando, FL	
Stockton Cogen Company	Sacramento, CA	
Syl Laskin	St. Cloud, MN	
Tecumseh EC	Topeka, KS	
Texas-New Mexico	San Antonio, TX	Closest Met Station (Dallas) received less precipitation than site location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant. Also average precipitation for the second closest Met Station was nearest to http://www.weather.com
Titus	Philadelphia, PA	
Trimble County	Cincinnati, OH	
Tyrone	Lexington, KY	
Valley	Madison, WI	
Vermilion	Chicago, IL	Closest Met Station (Indianapolis) receives more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.
Victor J Daniel Jr	Tallahassee, FL	Closest Met Station (New Orleans) receives much more precipitation (5.06” out of range) than the site location. Used second closest because only slightly above (3.4) expected precipitation range for plant.
W A Parish	Shreveport, LA	2 Closest Met Stations (Lake Charles & San Antonio) are more than 4” out of range. Used third closest because only slightly above (1.65”) expected precipitation range for plant.
W H Weatherspoon	Greensboro, NC	
W S Lee	Watkinsville, GA	
Wabash River	Indianapolis, IN	
Walter C Beckjord	Cincinnati, OH	
Wansley	Atlanta, GA	
Warrick	Indianapolis, IN	Closest Met Station (Nashville) receives 12.2” more precipitation than plant location. Used second closest Met Station because 5-year averages fell within expected precipitation range for the plant.

(continued)

Climate Center Assignments (continued)

Plant	Climate Center	Explanation If Not Closest Climate Center
Waukegan	Chicago, IL	
Weston	Madison, WI	
Widows Creek	Nashville, TN	
Will County	East St. Louis, IL	
Wyodak	Rapid City, SD	
Yates	Atlanta, GA	

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Attachment C-4: Waterbody Assignments and Flow

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
A B Brown	05140202014	OHIO R	Regular Reach	9167.38965	150031.6875
A/C Power- Ace Operations	18090205005	SEARLES L	Lake Shoreline		
Allen	08010211007	HORN LAKE CUTOFF	Lake Shoreline		
Alma	07040003009	MISSISSIPPI R	Regular Reach	5683.02002	25397.4707
Antelope Valley	10130201005	ANTELOPE CR	Start Reach	0	96.87
Arkwright	03070103007	OCMULGEE R	Regular Reach	428.79999	2708.53003
Asheville	06010105026	FRENCH BROAD R	Regular Reach	412.04999	1722.34998
Baldwin	07140204004	KASKASKIA R	Regular Reach	351.72	3832.12012
Barry	03160204014	MOBILE R	Regular Reach	7561.14014	63275.23828
Bay Front	07070005036	L SUPERIOR	Great Lakes Shoreline		
Bay Shore	04100010003	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
Belews Creek	03010103098	BELEWS L	Lake Shoreline		
Ben French	10120110010	CASTLE CR	Start Reach	2.96	18.62
Big Cajun 2	08070100005	MISSISSIPPI R	Regular Reach	100937.8125	466865.5625
Big Sandy	05070204008	BIG SANDY R	Regular Reach	152.02	5746.95996
Big Stone	07020001033	BIG STONE LAKE	Lake Shoreline		
Black Dog Steam Plant	07020012001	BLACK DOG LAKE	Lake Shoreline		
Blue Valley	10300101034	LITTLE BLUE R	Regular Reach	23.2	141.75
Bowen	03150104008	ETOWAH R	Regular Reach	413.13	2294.86011
Brandon Shores	02060003037	CURTIS BAY	Coastal Shoreline	0	0
Buck	03040103040	YADKIN R	Regular Reach	912.72998	4722.54004
Bull Run	06010207015	CLINCH R	Regular Reach	102.46	4732.3501
C D McIntosh Jr	03100205014	NO LAKE PARKER	Lake Shoreline		

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
C P Crane	02060003025	CURTIS BAY	Coastal Shoreline	0	0
Cape Fear	03030002001	HAW R	Regular Reach	58.98	1584.83997
Carbon	14060007018	PRICE R	Regular Reach	1.92	77
Cardinal	05030106033	OHIO R	Regular Reach	3391.62012	37533.17188
Cayuga	05120108001	WABASH R	Regular Reach	965.09003	10100.21973
Chalk Point	02060006009	PATUXENT R	Wide-River Shoreline	0	0
Cholla	15020008017	CHOLLA COOLING POND	Lake Shoreline		
Cliffside	03050105031	BROAD R	Regular Reach	332.17001	1510.08997
Clover	03010102027	ROANOKE R	Regular Reach	408.64001	2702.59009
Coal Creek	10130101018	UNKNOWN LAKE	Lake Shoreline		
Coleto Creek	12100303014	MARCELINAS CR	Start Reach	1.11	3.79
Colstrip	10100001108	ARMELLS CR, E FK	Start Reach	0	18.64
Conemaugh	05010007002	CONEMAUGH R	Regular Reach	194.53999	1553.52002
Conesville	05040004071	MUSKINGUM R	Regular Reach	447.98001	4707.08008
Council Bluffs	10230006004	MISSOURI R	Regular Reach	4402.58984	31444.83008
Crawford	07130011018	ILLINOIS R	Regular Reach	3444.66992	20788.71094
Crist	03140305001	ESCAMBIA R	Terminal Reach	845.46002	6772.5498
Cross	03050201022	DIVERS CANAL TO LAKE MOU	Lake Shoreline		
Cumberland	05130205017	CUMBERLAND R	Regular Reach	536.47998	25322.66016
Dale	05100205047	KENTUCKY R	Regular Reach	35.32	5213.06982
Dallman	07130007003	LAKE SPRINGFIELD	Lake Shoreline		
Dan E Karn	04080103005	L HURON U.S. SH SAGINAW BAY	Great Lakes Shoreline	0	0
Dan River	03010103014	DAN R	Regular Reach	358.12	1954.15002
Danskammer	02020008022	HUDSON R	Wide-River Shoreline	0	0
Dave Johnston	10180007005	N PLATTE R	Regular Reach	65.24	502.87
Dickerson	02070008013	POTOMAC R	Regular Reach	895.57001	10528.36035
Dolet Hills	11140206019	BAYOU PIERRE LAKE	Lake Shoreline		

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
Duck Creek	07130003010	L CHAUTAUQUA	Lake Shoreline		
Dunkirk	04120101003	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
E D Edwards	07130003018	ILLINOIS R	Regular Reach	2998.32007	13899.62988
E W Brown	05100205015	HERRINGTON LAKE	Lake Shoreline		
Eckert Station	04050004003	GRAND R	Regular Reach	73.47	484.28
Edgewater	04030101002	L MICHIGAN	Great Lakes Shoreline	0	0
Elmer W Stout	05120201005	WHITE R	Regular Reach	70.17	1429.92004
F B Culley	05140201001	OHIO R	Regular Reach	8728.7002	131543.0625
Fayette Power Prj	12090301003	CEDAR CREEK RESERVOIR	Lake Shoreline		
Flint Creek	11110103031	SWEPCO RSRVR,LT FLINT CK	Lake Shoreline		
Fort Martin	05020003001	MONONGAHELA R	Regular Reach	293.66	4497.75
Frank E Ratts	05120202003	WHITE R	Regular Reach	343.59	11525.13965
G G Allen	03050101009	CATAWBA R	Regular Reach	462.92001	2958.09009
Gadsden	03150106041	COOSA R	Regular Reach	1096.10999	9468
Gallatin	05130201006	OLD HICKORY L	Lake Shoreline		
Gen J M Gavin	05030202005	OHIO R	Regular Reach	4258.12012	55143.35938
Genoa	07060001017	MISSISSIPPI R	Regular Reach	6434.18018	29379.25
Gibson	05120113013	WABASH R	Regular Reach	2247.6001	26799.73047
Gorgas	03160109002	BLACK WARRIOR R, MULBERRY F	Lake Shoreline		
Green River	05110003001	GREEN R	Regular Reach	320.06	9752
Greene County	03160113011	BLACK WARRIOR R	Regular Reach	304.73001	9820.04004
H B Robinson	03040201042	L ROBERTSON	Lake Shoreline		
Hammond	03150105025	COOSA R	Regular Reach	1196.82996	6569.95996
Harllee Branch	03070101006	L SINCLAIR	Lake Shoreline		
Harrison	05020002008	WEST FORK R	Regular Reach	33.03	1038.32996
Hatfield's Ferry	05020005026	MONONGAHELA R	Regular Reach	479.79999	8278.94043
Hennepin	07130001026	ILLINOIS R	Regular Reach	3233.23999	13146.83984

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Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
Heskett	10130101001	MISSOURI R	Regular Reach	3461.55005	22744.26953
Holcomb	11030001001	ARKANSAS R	Regular Reach	0	197.92999
Homer City	05010007015	TWO LICK CR	Regular Reach	4.53	295.22
Hoot Lake	09020103002	OTTER TAIL R	Regular Reach	12.45	271.35999
Hugo	11140105041	KIAMICHI CR, N FK	Start Reach	2.55	53.16
Hunter	14060009034	ROCK CANYON CR	Start Reach	0	0.1
Huntington	14060009020	HUNTINGTON CR	Regular Reach	10.75	91.1
Intermountain		none		0	0
J H Campbell	04050002001	L MICHIGAN	Great Lakes Shoreline	0	0
J M Stuart	05090201024	OHIO R	Regular Reach	6767.47021	92214.6875
J R Whiting	04100001002	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
Jack McDonough	03130002044	CHATTAHOOCHEE R	Regular Reach	726.45001	2952.18994
Jack Watson	03170009034	BILOXI BAY	Coastal Shoreline	0	0
James H Miller Jr	03160111005	BLACK WARRIOR R, LOCUST FK	Lake Shoreline		
Jim Bridger	14040105011	UNKNOWN LAKE	Lake Shoreline		
John E Amos	05050008007	KANAWHA R	Regular Reach	1390.22998	14930.83984
John Sevier	06010104011	HOLSTON R	Regular Reach	633	4079.15991
Johnsonville	06040005007	KENTUCKY L	Lake Shoreline		
Joliet 29	07120004004	DES PLAINS R	Regular Reach	1029.93005	3809.69995
Keystone	05010006002	CROOKED CR	Regular Reach	30.72	422.14999
Killen Station	05090201024	OHIO R	Regular Reach	6767.47021	92214.6875
Kingston	06010207001	CLINCH R	Regular Reach	266.35999	7347.89014
Kraft	03060109007	SAVANNAH R	Regular Reach	3570.52002	12365
L V Sutton	03030005011	CAPE FEAR R	Regular Reach	619.95001	8594.57031
Lansing	07060001009	MISSISSIPPI R	Regular Reach	7684.02002	32253.15039
Laramie R Station	10180011002	LARAMIE R	Regular Reach	28.53	90.8
Lawrence EC	10270104021	KANSAS R	Regular Reach	403.81	6720.29004

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
Lee	03020201007	NEUSE R	Regular Reach	76.18	1657.39001
Leland Olds	10130101020	MISSOURI R	Regular Reach	4270.4502	21650.67969
Lon Wright	10220003048	RAWHIDE CR	Start Reach	0.94	11.59
Louisa	07080101003	MISSISSIPPI R	Regular Reach	15067.92969	54665.96094
Marion	05140204030	L OF EGYPT	Lake Shoreline		
Marshall	03050101015	L NORMAN	Lake Shoreline		
Martin Lake	12010002050	MARTIN LAKE	Lake Shoreline		
Mayo	03010104045	MAYO CR	Start Reach	5.99	61.03
Meramec	07140101014	MISSISSIPPI R	Regular Reach	33305	177021.1875
Merom	05120111011	TURTLE CR RESERVOIR	Lake Shoreline		
Miami Fort	05090203012	OHIO R	Regular Reach	6516.18994	98615.0625
Milton R Young	10130101024	NELSON LAKE AND MISSOURI RIVER	Lake Shoreline		
Mitchell - PA	05020005002	MONONGAHELA R	Regular Reach	848.58002	9284.13965
Mitchell - WV	05030106013	OHIO R	Regular Reach	3419.20996	38713.19922
Mohave	15030101011	COLORADO R	Regular Reach	1916.72998	12134.36035
Monroe	04100001002	L ERIE, U.S. SHORE	Great Lakes Shoreline	0	0
Morgantown	02070011051	POTOMAC R	Wide-River Shoreline	0	0
Mountaineer (1301)	05030202008	OHIO R	Regular Reach	4242.58984	54823.21094
Mt Storm	02070002027	STONY R RES	Lake Shoreline		
Muscatine Plant #1	07080101005	MISSISSIPPI R	Regular Reach	14573.71973	54469.48047
Muskogee	11110102012	ARKANSAS R	Regular Reach	227.57001	21258.39062
Neal North	10230001021	MISSOURI R	Regular Reach	4217.7998	29486.82031
Neal South	10230001021	MISSOURI R	Regular Reach	4217.7998	29486.82031
Nebraska City	10240001002	MISSOURI R	Regular Reach	5807.77002	36764.01172
New Castle	05030104002	BEAVER R	Regular Reach	268.48001	2425.32007
Newton	05120114006	NEWTON LAKE	Lake Shoreline		
North Omaha	10230006009	MISSOURI R	Regular Reach	4365.6499	31400.93945

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
Northeastern	11070105012	VERDIGRIS R	Regular Reach	3.85	2168.47998
Nucla	14030003012	SAN MIGUEL R	Regular Reach	8.1	307.64001
Oklaunion	11130302061	BOGGY CR	Start Reach	0.09	14.93
Paradise	05110003003	GREEN R	Regular Reach	316.59	9663.71973
Petersburg	05120202003	WHITE R	Regular Reach	343.59	11525.13965
Pleasant Prairie	07120004012	L MICHIGAN AND J	Lake Shoreline		
Port Washington	04030101002	L MICHIGAN	Great Lakes Shoreline	0	0
Portland	02040105012	DELAWARE R	Regular Reach	1995.12	9089.00977
Possum Point	02070011074	POTOMAC R	Wide-River Shoreline	0	0
Potomac River	02070010025	POTOMAC R	Artificial Open Water Reach	919.89001	11721.87988
Presque Isle	04020105002	L SUPERIOR, U.S. SHORE	Great Lakes Shoreline	0	0
R Gallagher	05140101001	OHIO R	Regular Reach	7634.39014	119152.1875
R M Schahfer	07120001012	KANAKEE R	Regular Reach	458.92001	1410.56006
Reid Gardner	15010012006	MUDDY R	Regular Reach	0.68	19.22
Richard Gorsuch	05030202039	OHIO R	Regular Reach	4079.81006	48956.14062
Riverbend	03050101012	CATAWBA R	Regular Reach	412.28	2623.09009
Rodemacher	11140207020	RODEMACHER LAKE	Lake Shoreline		
Roxboro	03010104034	HYCO L	Lake Shoreline		
Sandow	12070102012	ALCOA LAKE	Lake Shoreline		
Scherer	03070103012	OCMULGEE R	Start Reach	655.48999	2490.72998
Shawnee	05140206009	OHIO R	Regular Reach	21748.59961	288452.1875
Shawville	02050201002	SUSQUEHANNA R, W BR	Regular Reach	96.9	1947.33997
Sheldon	10240008030	UNKNOWN LAKE	Lake Shoreline		
South Oak Creek	04040002004	L MICHIGAN	Great Lakes Shoreline	0	0
Springerville	15020002025	*A	Start Reach	0	2.49
St Johns River Power	03080103003	ST JOHNS R	Wide-River Shoreline	0	0
Stanton Energy Ctr	03080101036	ECOHLOCKHATCHEE R	Start Reach	5.95	131.42999

(continued)

Waterbody Assignments and Flow (continued)

Plant	CUSEG	Nearest Reach	Reach_Type	QLOW	QMEAN
Stockton Cogen Company	18040002005	LITTLEJOHNS CR	Start Reach	0.21	50.61
Syl Laskin	04010201034	COLBY L AND PARTRIDGE R	Lake Shoreline		
Tecumseh EC	10270102003	KANSAS R	Regular Reach	388.51999	5923.74023
Texas-New Mexico	12070101008	LITTLE BRAZOS R	Start Reach	0.55	139.05
Titus	02040203010	SCHUYLKILL R	Regular Reach	91.25	1880.77002
Trimble County	05140101007	OHIO R	Regular Reach	7524.29004	117896.3125
Tyrone	05100205013	KENTUCKY R	Regular Reach	154.36	7097.54004
Valley	04040003001	MILWAUKEE R	Terminal Reach	10.71	540.60999
Vermilion	05120109006	VERMILION R, M FK	Regular Reach	3.45	340.35999
Victor J Daniel Jr	03170006007	PASCAGOULA R	Regular Reach	1256.55005	12878.25
W A Parish	12070104021	SMITHERS L	Lake Shoreline		
W H Weatherspoon	03040203016	LUMBER R	Regular Reach	97.9	865.13
W S Lee	03050109066	SALADA R	Regular Reach	20.68	461.51001
Wabash River	05120111018	WABASH R	Regular Reach	985.53998	10551.67969
Walter C Beckjord	05090201001	OHIO R	Regular Reach	6416.77002	92084.0625
Wansley	03130002032	CHATTAHOOCHEE R	Regular Reach	702.71002	4400.72021
Warrick	05140201022	LITTLE PIGEON CR	Regular Reach	61.57	1149.60999
Waukegan	04040002002	L MICHIGAN	Great Lakes Shoreline	0	0
Weston	07070002023	WISCONSIN R	Regular Reach	1069.30005	3484.32007
Widows Creek	06030001049	TENNESSEE R	Regular Reach	7221.95996	38237.07031
Will County	07110009002	WOOD R	Start Reach	29	87.81
Wyodak	10120201038	DONKEY CR	Start Reach	0	4.4
Yates	03130002061	CHATTAHOOCHEE R	Regular Reach	702.21997	4063.29004

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Appendix D. MINTEQA2 Nonlinear Sorption Isotherms

D.1 Overview of MINTEQA2 Modeling

Chemicals in leachate can be subject to complex geochemical interactions in soil and groundwater, which can strongly affect their rate of transport in the subsurface. The U.S. Environmental Protection Agency's Composite Model for Leachate Migration with Transformation Products (EPACMTP) treats these interactions as equilibrium sorption processes. The equilibrium assumption means that the sorption process occurs instantaneously, or at least very quickly relative to the time scale of constituent transport. Although sorption—or the attachment of leachate constituents to solid soil or aquifer particles—may result from multiple chemical processes, EPACMTP lumps these processes together into an effective soil-water partition coefficient (K_d). The retardation factor (R) accounts for the effects of equilibrium sorption of dissolved constituents onto the solid phase. R, a function of the constituent-specific K_d and the soil or aquifer properties, is calculated as:

$$R = 1 + \frac{\rho_b \times K_d}{\Phi} \qquad \text{(D-1)}$$

where

R = Retardation factor
ρ_b = Soil or aquifer bulk density (mg)
K_d = Solid-water partition coefficient (g/cm^3)
ϕ = Water content (in unsaturated zone) or porosity (in saturated zone).

An isotherm is an expression of the equilibrium relationship between the aqueous concentration and the sorbed concentration of a metal (or other constituent) at a constant temperature. For metals, EPACMTP accounts for more complex geochemical reactions by using effective sorption isotherms generated using EPA's geochemical equilibrium speciation model for dilute aqueous systems, MINTEQA2 (U.S. EPA, 1991).

The MINTEQA2 model is used to generate one set of isotherms for each metal reflecting the range in geochemical environments expected at waste sites across the nation. The variability in geochemical environments at coal combustion waste (CCW) sites across the country is represented by five geochemical master variables (groundwater composition, pH, concentration of iron oxide adsorption sites, leachate ionic strength, and concentration of dissolved and particulate natural organic matter), and the MINTEQA2 modeling is repeated (separately for each metal) for numerous combinations of master variable settings. This procedure results in nonlinear K_d versus aqueous metal concentration curves for combinations of master variable settings spanning the range of reasonable values (U.S. EPA 2003a).

For each metal, the resulting set of isotherms is tabulated into a supplementary input data file for use by the EPACMTP model, hereafter referred to as an "empirical nonlinear isotherm." In the fate and transport modeling for a particular metal, EPACMTP is executed and the national probability distributions for these five master variables form the basis for the Monte Carlo selection of the appropriate adsorption isotherm.

In modeling metals transport in the unsaturated zone, EPACMTP uses a range of K_d values from the nonlinear sorption isotherms. However, in modeling metals transport in the saturated zone, EPACMTP selects the lowest from all available K_d values corresponding to concentrations less than or equal to the maximum water table concentration. For more details see the *EPACMTP Technical Background Document* (U.S. EPA, 2003b).

This simplification in the saturated zone is required for all solution options and is based on the assumption that after dilution of the leachate plume in groundwater, the concentrations of metals will typically be in a range where the isotherm is approximately linear. However, this assumption may not be valid when the metal concentrations in the leachate are exceedingly high. Although EPACMTP is able to account for the effect of the geochemical environment at a site on the mobility of metals, the model assumes that the geochemical environment at a site is constant and not affected by the presence of the leachate plume. In reality, the presence of a leachate plume may alter the ambient geochemical environment.

D.2 Previous CCW Metals Modeling Effort

In a previous risk assessment for fossil fuel combustion wastes (FFCWs) conducted in 1998 (U.S. EPA, 1998), sorption isotherms generated using MINTEQA2 were used in EPACMTP to account for metal partitioning. However, these isotherms were not calculated specifically for use in FFCW modeling—they had been computed using MINTEQA2 in 1995 for use in modeling support for the Hazardous Waste Identification Rule (HWIR).

The disposal scenario for HWIR was the industrial Resource Conservation and Recovery Act (RCRA) Subtitle D nonhazardous waste landfill. In fact, the MINTEQA2 modeling that produced the isotherms had originally been designed to represent municipal solid waste landfills, and leachate from those landfills had been sampled so that appropriate forms of leachate organic acids at various concentrations could be included in the modeling. For the HWIR analysis, the scenario was changed to industrial Subtitle D, and only the isotherms corresponding to low concentrations of the leachate organic acids were used for HWIR modeling. The same isotherms were used in the 1998 FFCW risk assessment. As in the HWIR modeling, only the isotherms corresponding to the lowest setting of leachate organic carbon were used.

In 1999, EPA received review comments concerning the use of the industrial Subtitle D metal partitioning isotherms in the 1998 risk assessment. The most comprehensive review was prepared by Charles Norris and Christina Hubbard on behalf of the Environmental Defense Fund and other environmental advocacy groups (Norris and Hubbard, 1999). The Norris and Hubbard report criticized the 1998 risk assessment for using MINTEQA2 isotherms designed for a different scenario (nonhazardous industrial landfills). Norris and Hubbard also offered 20 specific criticisms on the input parameters and other factors involved in the MINTEQA2 modeling. EPA responded by evaluating each of these criticisms through review and assessment

of MINTEQA2 input values, model sensitivity tests, and consultations with experts. This review is documented in U.S. EPA (2000, 2001a). The evaluation of the Norris and Hubbard comments resulted in suggested revisions in the MINTEQA2 modeling strategy, as described in U.S. EPA (2001b).

Based on a review of available information on CCW leachate composition and an analysis of the potential effects of this composition on metals mobility, EPA (U.S. EPA, 2001b) also determined that if MINTEQA2 is to be used at CCW sites, leachate from CCW facilities should be studied to look for trends in composition, especially with regard to the concentrations of constituents that may

- Contribute to elevated groundwater pH
- Compete with the contaminant metal for sorption sites and thus result in reduced metal sorption (e.g., Ca, Mg, SO_4, other metals)
- Complex with the contaminant metal so that the metal is less likely to be sorbed (e.g., SO_4, CO_3, organic ligands)
- Precipitate with the contaminant metal (e.g., SO_4, CO_3).

D.3 MINTEQA2 Modeling Revisions for CCW Risk Assessment

Many of the suggested revisions from U.S. EPA (2001b) were implemented in the MINTEQA2 modeling for the current CCW risk assessment. Some of the suggested revisions were not implemented, either because they are not applicable (e.g., organic carbon assumptions should not be changed because CCW leachate has negligible organic carbon) or because models or data were not adequate to carry forth the recommendation. These revisions are discussed in greater detail in U.S. EPA (2003c).

In addition to revising the MINTEQA2 model, EPA compiled leachate characteristics into the CCW constituent database (see Appendix A) and statistically analyzed these data to identify three chemically distinct CCW leachate types: conventional CCW (including ash and flue gas desulfurization [FGD] sludge), codisposed CCW and coal cleaning wastes, and fluidized bed combustion (FBC) waste. Leachate concentration ranges for major ions (e.g., Ca, SO_4, Mg, Na, Cl, etc.) and pH were developed for each of these waste types and were used to represent CCW leachate during MINTEQA2 modeling.

As needed, sorption reactions were included for those CCW constituents known to undergo significant sorption. Including elevated concentrations of leachate constituents and their corresponding sorption reactions in the MINTEQA2 model allows for full competition with the contaminant metal for sorption sites. The metal solubilizing effect through complexation between the contaminant metal and dissolved ligands is also included, as is the potential for metal precipitation. Because precipitation of the metal can serve to attenuate the transportable concentration, the equilibrium fraction in all three phases (dissolved, sorbed, and precipitated) were stored and made available for use by EPACMTP. The precipitated fraction was used to develop a solubility limit that was used during EPACMTP modeling (U.S. EPA, 2003c).

D.4 MINTEQA2 Modeling for CCW Risk Assessment

The expected natural variability in K_d for a particular metal was represented during the MINTEQA2 modeling effort by varying the input parameters that most impact K_d: groundwater type (carbonate or noncarbonate), pH, concentration of aquifer sorbents, composition and concentration level of CCW leachate, and concentration of the contaminant metal. The natural pH range for the two groundwater types was sampled from a range of 7 to 8 for carbonate aquifers and 4 to 10 for noncarbonate aquifers (U.S. EPA, 2003c).

In addition, CCW leachate ranges from acidic (pH < 2) to highly alkaline (pH > 12) and can impact vadose zone and groundwater pH. To account for this possibility, the CCW leachate/ groundwater system was equilibrated at a series of pH values that span the range of expected variability in mixed CCW leachate-groundwater systems (U.S. EPA, 2003c).

To account for the variability in the sorption capacity of soil and aquifer materials, the soil and groundwater systems were equilibrated with various concentrations of two commonly occurring natural sorbents: ferric (iron) oxyhydroxide (FeOx) and particulate organic matter (POM). CCW leachate can include elevated concentrations of inorganic constituents such as calcium, sulfate, sodium, potassium, and chloride, which may reduce sorption of metals due to competition for sorption sites or complexation with metals in solution. To account for this effect, these leachate components were added to the MINTEQA2 model inputs at concentrations representative of the three CCW waste types (conventional CCWs, codisposed CCW and coal cleaning wastes, and FBC wastes). This new MINTEQA2 master variable is termed leachate "richness" or ionic strength (U.S. EPA, 2003c).

The results of each MINTEQA2 model run were compiled as the equilibrium distribution of the contaminant metal among dissolved, sorbed, and precipitated fractions for each metal concentration, and were saved in a separate file indexed with the settings of all variables used to define the system. These files were produced for all possible values for the variables defining the system, and were compiled into a database of indexed K_d values for use in the EPACMTP fate and transport model (U.S. EPA, 2003c).

D.5 EPACMTP Modeling Revisions to Accommodate MINTEQA2 Updates

EPA updated EPACMTP to support the new system variable (leachate ionic strength) for isotherm selection, to address issues regarding the impacts of leachate pH on ambient soil and aquifer pH, and to address issues regarding solubility limits for metals in solution. A brief description of these model changes are discuss below, with more detail provided in U.S. EPA (2003d).

Ionic Strength. A new system or "master" variable was added to include ionic strength as a key for choosing the representative isotherm from the database for both the unsaturated and saturated zones.

Leachate Effects on Geochemical Environment. These effects were addressed in EPACMTP under the following constraints: (1) no significant impairment of the computational efficiency for probabilistic applications; (2) data requirements limited to readily available data;

and (3) a scientifically defensible approach, given significant uncertainties with respect to the true impacts of leachate pH on the subsurface. Two modifications to the EPACMTP were considered: (1) determine the governing pH in the soil column (either the pH of the leachate or the native soils); and (2) determine the pH of the saturated zone as a result of the infiltrating leachate.

The approach selected for determining the governing pH of the soil column (vadose zone) beneath the waste management unit (WMU) compares the operational life of the WMU (the duration of leaching) to an estimate of the first arrival time of the contaminant front at the water table (a surrogate for the residence time of the contaminant in the soil column). If the operational life of the WMU is *relatively* long compared to the time required for the contaminant to migrate to the water table, there is a high likelihood that the leachate permeates the soil column and that the pH environment is governed by the leachate.

Conversely, a relatively short operational life and retarded contaminant migration would favor ambient soil pH conditions. An analysis of the relationship between operational life and travel time indicated that a ratio of approximately 5 (operational life over travel time) would, in many cases, result in a balanced selection of cases where leachate pH governs versus cases where soil pH governs over approximately 10,000 Monte Carlo iterations.

For each iteration of EPACMTP, the operational life was compared to a travel-time estimate based on a K_d averaged from isotherms selected based on the leachate pH and soil pH. If the ratio was greater than 5, the pH of the leachate was assumed to govern, and the pH of the leachate was used to select the isotherm for transport in the unsaturated zone. If the ratio was less than 5, the soil pH was used to select the isotherm.

In the saturated zone, the impacts of leachate pH were handled using a simple homogeneous mixing calculation. The volume of leachate released from the WMU was mixed with the volume of the aquifer that was likely to be impacted by a plume. The resulting mixed pH was used to select the isotherm for transport in the saturated zone with one limitation: in carbonate environments, the mixed pH in the aquifer was not allowed to drop below a pH of 6. Such acid conditions would likely result in significant dissolution of the soil matrix.

Metal Solubility Limits. As mentioned above, each sorption isotherm comprises equilibrium concentrations of the three contaminant phases (dissolved, sorbed, and precipitated) over a range of total concentration values. An examination of the change in the dissolved-phase concentrations relative to changes in the total concentration in any isotherm reveals solubility behavior for that contaminant: if the dissolved component does not change with increasing total concentration, a solubility limit has been achieved. If, however, the dissolved component increases along with the total concentration, then there is capacity for more dissolved mass in the groundwater or soil porewater.

EPACMTP uses this information (contained in each isotherm file) to determine if a solubility limit should be imposed in the saturated zone. Once an isotherm has been selected (after pH considerations have been addressed), the equilibrium states corresponding to the three highest total concentrations are examined. If the dissolved concentration changes more than one tenth of one percent over the last three points, then EPACMTP assumes there is no solubility

limit. If the change in dissolved concentration is less than one tenth of one percent, EPACMTP assumes a solubility limit has been reached and caps the concentration of the leachate entering the saturated zone at the water table to that limit.

D.5 References

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Appendix E. Surface Water, Fish Concentration, and Contaminant Intake Equations

This appendix presents the equations used to model surface water and fish concentrations and intake of drinking water and fish. These equations are presented in the following attachments:

- Attachment E-1 provides the equations comprising the surface water equilibrium partitioning model, including equations that estimate steady state concentrations in the water column (dissolved and total) and sediments.
- Attachment E-2 provides the equations that use bioconcentration factors (BCFs) to calculate fish tissue concentrations from total.
- Attachment E-3 provides the equations used to calculate daily contaminant intake rates from drinking water and fish consumption.

E.1 Aluminum Surface Water Precipitation

Because the fate and transport of aluminum is controlled more by solubility than by sorption in surface water, the surface water model includes algorithms to estimate aluminum concentrations in the water column and sediments by accounting for precipitation and fallout of aluminum in the water column. These calculations proceed in a stepwise fashion, as follows.

Step 1. Initially, assume all influent aluminum is dissolved in the water column.

Fraction in water column (fwater) = 1
Fraction in sediment layer (fbenth) = 0
Fraction dissolved (fd) = 1

Total water column concentration (Cwctot) = dissolved water column concentration (Cwd).

Step 2. Compare the dissolved water column concentration (Cwd) to the maximum soluble concentration (Csol) calculated in MINTEQA2 for the waterbody pH (see Section 3.5.4, Table 3-6 for aluminum solubilities and Appendix C, Section C.6.3, Table C-11 for waterbody pH).

Step 3. If the dissolved water concentration (Cwd) is greater than the solubility limit (Csol), reset the dissolved water concentration to the solubility limit, and precipitate and settle out the excess aluminum to the benthic sediment layer.

```
If Cwctot > Csol, then
        Fwater  =  Csol / Cwctot
        Fbenth  =  (Cwctot - Csol) / Cwctot
          Cwbs  =  (Cwctot - Csol) * dwc / db
         Cwtot  =  Cwctot * dwc / dz
           Cdw  =  Csol
        Cwctot  =  Csol
Else
           Cdw  =  Cwctot
          Cwbs  =  0
         Cwtot  =  Cwctot * rsParam!dwc / rsParam!dz
End If
```

where:

Cdw	=	issolved waterbody concentration
Csol	=	maximum soluble concentration
Cwbs	=	total concentration in bed sediment
Cwtot	=	total waterbody concentration from loading
db	=	depth of the upper benthic layer
dwc	=	depth of the water column
dz	=	depth of the waterbody
fbenth	=	fraction in sediment layer
fd	=	fraction dissolved
fwater	=	fraction in water column

Table E-1-1. Fraction of Contaminant in Water Column (unitless)

f_{Water}

$$d_w = d_z - d_b$$

$$f_{Water} = \frac{\left[1 + \left(K_{dsw} \times TSS \times 0.000001\right)\right] \times \frac{d_w}{d_z}}{\left[\left[1 + \left(K_{dsw} \times TSS \times 0.000001\right)\right] \times \frac{d_w}{d_z}\right] + \left[\left(bsp + K_{dbs} \times bsc\right) \times \frac{d_b}{d_z}\right]}$$

Name	**Description**	**Value**
bsc	Bed sediment particle concentration (g/cm^3) or (kg/L)	1
bsp	Bed sediment porosity (cm^3/cm^3)	0.6
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
K_{dbs}	Sedment-water partition coefficient (mL/g)	Chemical Data; See Section 3
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	Chemical Data; See Section 3
TSS	Total suspended solids (mg/L)	Site Data; See Appendix C
0.000001	Conversion factor (L/ml)(g/mg)	

Table E-1-2. Fraction of Contaminant in Benthic Sediments (unitless)

f_{Benth}

$$f_{Benth} = \frac{(bsp + K_{dbs} \times bsc) \times \frac{d_b}{d_z}}{\left[(1 + K_{dsw} \times TSS \times 0.000001) \times \frac{d_W}{d_z}\right] + \left[(bsp + K_{dbs} \times bsc) \times \frac{d_b}{d_z}\right]}$$

Name	**Description**	**Value**
bsc	Bed sediment particle concentration (g/cm^3) or (kg/L)	1
bsp	Bed sediment porosity (cm^3/cm^3)	0.6
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
K_{dbs}	Sedment-water partition coefficient (mL/g)	Chemical Data; See Section 3
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	Chemical Data; See Section 3
TSS	Total suspended solids (mg/L)	Site Data; See Appendix C
0.000001	Conversion factor (L/ml)(g/mg)	

Table E-1-3. Dissolved Fraction (unitless)

f_d

$$f_d = \frac{1}{1 + K_{dsw} \times TSS \times 0.000001}$$

Name	Description	Value
K_{dsw}	Suspended sediment-water partition coefficient (mL/g)	Chemical Data; See Section 3
TSS	Total suspended solids (mg/L)	Site Data; See Appendix C
0.000001	Conversion factor (L/ml)(g/mg)	

Table E-1-4. Water Concentration Dissipation Rate Constant (1/d)

K_{wt}

$$K_{wt} = \left(f_{Water} \times f_d \times k_{vol}\right) + \left(f_{benth} \times K_b\right) + \left(f_{Water} \times k_{sw}\right) + \left(f_{benth} \times k_{sed}\right) + k_h$$

$$K_b = \frac{WB}{d_b}$$

$$k_{vol} = \frac{K_v}{d_w}$$

Name	Description	Value
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
F_b	Fraction of contaminant in benthic sediments (unitless)	Calculated
f_d	Dissolved fraction (unitless)	Calculated
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated
K_b	Benthic burial rate constant (1/day)	Calculated
k_h	Hydrolysis rate (1/day)	0
k_{sed}	Degradation rate for sediment (1/day)	0
k_{sw}	Degradation rate for water column (1/day)	0
K_v	Diffusion transfer rate (m/day)	Calculated (mercury only)
k_{vol}	Water column volatilization rate constant (1/day)	Calculated (mercury only)
WB	Rate of Burial (m/day)	0

Table E-1-5. Total Waterbody Concentration from Loading (g/m^3 or mg/L)

Cw_{Tot}

$$V = Area_{WB} \times d_z$$

$$Cw_{Tot} = \frac{L_{total}}{V_{fx} \times f_{Water} \times \frac{d_z}{d_w} + K_{wt} \times V}$$

Name	Description	Value
$Area_{WB}$	Area of the waterbody (m^2)	Site Data; See Appendix C
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated
K_{wt}	Water Concentration Dissipation Rate Constant (1/day)	Calculated
L_{Total}	Total waterbody load (g/day)	Calculated By EPACMTP
V	Flow independent mixing volume (m^3)	Calculated
V_{fx}	Waterbody annual flow mixing volume (m3/day)	Site Data; See Appendix C

Table E-1-6. Total Water Column Concentration (g/m^3 or mg/L)

C_{wcTot}

$$d_w = d_z - d_b$$

$$C_{wcTot} = C_{wTot} \times f_{water} \times \frac{d_z}{d_w}$$

Name	Description	Value
Cw_{Tot}	Total Waterbody Concentration from Loading (g/m^3 or mg/L)	Calculated
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated

Table E-1-7. Dissolved Waterbody Concentration (mg/L)

C_{dw}

$$d_w = d_z - d_b$$

$$C_{dw} = Cw_{Tot} \times f_{Water} \times f_d \times \frac{d_Z}{d_w}$$

Name	Description	Value
Cw_{Tot}	Total Waterbody Concentration from Loading (g/m^3 or mg/L)	Calculated
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated
f_d	Dissolved fraction (unitless)	Calculated
f_{Water}	Fraction of contaminant in water column (unitless)	Calculated

Table E-1-8. Total Concentration in Bed Sediment (g/m^3 or mg/L)

C_{wbs}

$$d_z = d_w + d_b$$

$$C_{bs} = C_{wTot} \times f_{benth} \times \frac{d_z}{d_b}$$

Name	Description	Value
Cw_{Tot}	Total Waterbody Concentration from Loading (g/m^3 or mg/L)	Calculated
d_b	Depth of upper benthic layer (m)	0.03
d_w	Depth of water column (m)	Site Data; See Appendix C
d_z	Depth of the waterbody (m)	Calculated

Table E-2-1. Concentration in Fish at Different Trophic Levels (mg/kg)

C_{fish}

For Non-Volatile Metals:

$$C_{fish} = Cw_{tot} \times BCF$$

Name	Description	Value
BCF	Bioconcentration factor for specified trophic level (L/kg)	Chemical Data; See Section 3
C_{dw}	Dissolved waterbody concentration (mg/L)	Calculated
Cw_{Tot}	Total waterbody concentration from loading (g/m^3 or mg/L)	Calculated
0.15	Fraction of dissolved mercury assumed to be methyl mercury (unitless)	

Table E-2-2. Average Fish Fillet Concentration Ingested by Humans (mg/kg)

C_{fish_fillet}

$$C_{fish\_fillet} = F_{T3} \times C_{fishT3F} + F_{T4} \times C_{fishT4F}$$

Name	Description	Value
$C_{fishT3F}$	Concentration of contaminant in fish at different trophic levels (mg/kg)	Calculated
$C_{fishT4F}$	Concentration of contaminant in fish at different trophic levels (mg/kg)	Calculated
F_{T3}	Fraction of trophic level 3 intake (unitless)	0.36
F_{T4}	Fraction of trophic level 4 intake (unitless)	0.64

Table E-3-1. Contaminant Intake from Drinking Water (mg/kg-d)

Idw

$$I_{dw} = \frac{C_{dw} \times CR_{dw} \times F_{dw}}{BW * 1000}$$

Name	**Description**	**Value**
BW	Body weight (kg)	Exposure Data; See Appendix F
C_{dw}	Dissolved waterbody concentration (mg/L)	Calculated
CR_{dw}	Consumption rate of water (mL/day)	Exposure Data; See Appendix F
F_{dw}	Fraction of drinking water ingested that is contaminated (unitless)	1
1000	Conversion factor (mL/L)	

Table E-3-2. Daily Intake of Contaminant from Fish Ingestion (mg/kg BW/day)

I_{fish}

$$I_{fish} = \frac{C_{fish\_fillet} \times CR_{fish} \times F_{fish}}{1000 \times BW}$$

Name	**Description**	**Value**
BW	Body weight (kg)	Exposure Data; See Appendix F
C_{fish_fillet}	Average fish fillet concentration ingested by humans (mg/kg)	Calculated
CR_{fish}	Consumption rate of fish (g WW/day)	Exposure Data; See Appendix F
F_{fish}	Fraction of fish intake from contaminated source (unitless)	1
1000	Conversion factor (g/kg)	

Appendix F. Human Exposure Factors

Exposure factors are data that quantify human behavior patterns (e.g., ingestion rates of fish and drinking water) and characteristics (e.g., body weight) that affect a person's exposure to environmental contaminants. These data can be used to construct realistic assumptions concerning an individual's exposure to and subsequent intake of a contaminant in the environment. The exposure factors data also enable the U. S. Environmental Protection Agency (EPA) to differentiate the exposures of individuals of different ages (e.g., a child vs. an adult). The derivation and values used for the human exposure factors in this risk assessment are described below, and the exposure factors selected for the probabilistic analyses are also presented.

F.1 Exposure Parameters Used in Probabilistic Analysis

F.1.1 Introduction

The general methodology for collecting human exposure data for the probabilistic analysis relied on the *Exposure Factors Handbook*, or EFH (U.S. EPA, 1997a-c), which was used in one of three ways:

1. When EFH percentile data were adequate (most input variables), maximum likelihood estimation was used to fit selected parametric models (gamma, lognormal, Weibull, and generalized gamma) to the EFH data. The chi-square measure of goodness of fit was then used to choose the best distribution. Parameter uncertainty information (e.g., for averages, standard deviations) also was derived using the asymptotic normality of the maximum likelihood estimate or a regression approach.

2. When EFH percentile data were not adequate for statistical model fitting (a few variables), models were selected on the basis of results for other age cohorts or, if no comparable information was available, by assuming lognormal as a default distribution and reasonable coefficients of variation (CVs).

3. When data were not adequate for either 1 or 2 above, variables were fixed at EFH-recommended mean values or according to established EPA policy.

Table F-1 lists all of the parameters used in the probabilistic analysis. Both fixed variables and the values used to define distributed data are provided.

Probabilistic risk analyses involve "sampling" values from probability distribution functions (PDFs) and using the values to estimate risk. In some cases, distributions are infinite, and there is a probability, although very small, that very large or very small values might be selected from the distributions. Because selecting extremely large or extremely small values is unrealistic (e.g., the range of adult body weights is not infinite), maximum and minimum values

were imposed on the distributions. The minimum and maximum values are included in Table F-1.

F.1.2 Exposure Parameter Distribution Methodology

This section describes how stochastic or distributed input data for each exposure factor were collected and processed. Exposure parameter distributions were developed for use in the Monte Carlo analysis. For most variables for which distributions were developed, exposure factor data from the EFH were analyzed to fit selected parametric models (i.e., gamma, lognormal, Weibull). Steps in the development of distributions included preparing data, fitting models, assessing fit, and preparing parameters to characterize distributional uncertainty in the model inputs.

For many exposure factors, EFH data include sample sizes and estimates of the following parameters for specific receptor types and age groups: mean, standard deviation, standard error, and percentiles corresponding to a subset of the following probabilities: 0.01, 0.02, 0.05, 0.10, 0.15, 0.25, 0.50, 0.75, 0.85, 0.90, 0.95, 0.98, and 0.99. These percentile data, where available, were used as a basis for fitting distributions. Although in no case were all of these percentiles actually provided for a single factor, seven or more are typically present in the EFH data. Therefore, using the percentiles is a fuller use of the available information than fitting distributions simply based on the method of moments (e.g., selecting models that agree with the data mean and standard deviation). For some factors, certain percentiles were not used in the fitting process because sample sizes were too small to justify their use. Percentiles were used only if at least one data point was in the tail of the distribution. If the EFH data repeated a value across several adjacent percentiles, only one value (the most central or closest to the median) was used in most cases (e.g., if both the 98th and 99th percentiles had the same value, only the 98th value was used).

The EFH does not use standardized age cohorts across exposure factors. Different exposure factors have data reported for different age categories. Therefore, to obtain the percentiles for fitting the four standardized age cohorts (i.e., ages 1 to 5, 6 to 11, 12 to 19, and more than 20), each EFH cohort-specific value for a given exposure factor was assigned to one of these four cohorts. When multiple EFH cohorts fit into a single cohort, the EFH percentiles were averaged within each cohort (e.g., data on 1- to 2-year-olds and 3- to 5-year-olds were averaged for the 1- to 5-year-old cohort). If sample sizes were available, weighted averages were used, with weights proportional to sample sizes. If sample sizes were not available, equal weights were assumed (i.e., the percentiles were simply averaged).

Table F-1. Summary of Exposure Parameters Used in Probabilistic Analysis

Parameter	Units	Variable Type	Constants	Mean (or shape)	Std Dev (or scale)	Minimum	Maximum	Reference
Averaging time for carcinogens	yr	Constant	7.00E+01					U.S. EPA (1989)
Body weight (adult)	kg	Lognormal		7.12E+01	1.33E+01	1.50E+01	3.00E+02	U.S. EPA (1997a); Tables 7-2, 7-4, 7-5
Body weight (child 1)	kg	Lognormal		1.55E+01	2.05E+00	4.00E+00	5.00E+01	U.S. EPA (1997b); Tables 7-3, 7-6, 7-7
Body weight (child 2)	kg	Lognormal		3.07E+01	5.96E+00	6.00E+00	2.00E+02	U.S. EPA (1997a); Tables 7-3, 7-6, 7-7
Body weight (child 3)	kg	Lognormal		5.82E+01	1.02E+01	1.30E+01	3.00E+02	U.S. EPA (1997a); Tables 7-3, 7-6, 7-7
Consumption rate: fish (adult, child)	g/d	Lognormal		6.48E+00	1.99E+01	0.00E+00	1.50E+03	U.S. EPA (1997b); Table 10-64
Exposure duration (adult resident)	yr	Weibull		1.34E+00	1.74E+01	1.00E+00	5.00E+01	U.S. EPA (1999) (ACS)
Exposure duration (child)	yr	Weibull		1.32E+00	7.06E+00	1.00E+00	5.00E+01	U.S. EPA (1999) (ACS)
Exposure frequency (adult resident)	d/yr	Constant	3.50E+02					U.S. EPA Policy
Fraction contaminated: drinking water	Fraction	Constant	1.00E+00					U.S. EPA Policy
Fraction contaminated: fish	Fraction	Constant	1.00E+00					U.S. EPA Policy
Fraction of fish consumed that is trophic level (T3) fish	Fraction	Constant	3.60E-01					U.S. EPA (1997b); Table 10-66
Fraction of fish consumed that is trophic level 4 (T4) fish	Fraction	Constant	6.40E-01					U.S. EPA (1997b); Table 10-66
Ingestion rate: drinking water (adult resident)	mL/d	Gamma		3.88E+00	3.57E+02	1.04E+02	1.10E+04	U.S. EPA (1997a); Table 3-6
Ingestion rate: drinking water (child 1 resident)	mL/d	Gamma		2.95E+00	2.37E+02	2.60E+01	3.84E+03	U.S. EPA (1997a); Table 3-6
Ingestion rate: drinking water (child 2 resident)	mL/d	Gamma		3.35E+00	2.35E+02	3.40E+01	4.20E+03	U.S. EPA (1997a); Table 3-6
Ingestion rate: drinking water (child 3 resident)	mL/d	Gamma		2.82E+00	3.42E+02	3.30E+01	5.40E+03	U.S. EPA (1997a); Table 3-6

Because the EFH data are always positive and are almost always skewed to the right (i.e., have a long right tail), three two-parameter probability models commonly used to characterize such data (gamma, lognormal, and Weibull) were selected. In addition, a three-parameter model (generalized gamma) was used that unifies them[1] and allows for a likelihood ratio test of the fit of the two-parameter models. However, only the two-parameter models were selected for use in the analysis because the three-parameter generalized gamma model did not significantly improve the goodness of fit over the two-parameter models. This simple setup constitutes a considerable improvement over the common practice of using a lognormal model in which adequate EFH data are available to support maximum likelihood estimation.

Lognormal, gamma, Weibull, and generalized gamma distributions were fit to each factor data set using maximum likelihood estimation (Burmaster and Thompson, 1998). When sample sizes were available, the goodness of fit was calculated for each of the four models using the chi-square test (Bickel and Doksum, 1977). When percentile data were available but sample sizes were unknown, a regression F-test for the goodness of fit against the generalized gamma model was used. For each of the two-parameter models, parameter uncertainty information (i.e., mean, standard deviation, scale, and shape) was provided as parameter estimates for a bivariate normal distribution that could be used for simulating parameter values (Burmaster and Thompson, 1998). The information necessary for such simulations includes estimates of the two model parameters, their standard errors, and their correlation. To obtain this parameter uncertainty information, the asymptotic normality of the maximum likelihood estimate (Burmaster and Thompson, 1998) was used when sample sizes were available, and a regression approach was used when sample sizes were not available (Jennrich and Moore, 1975; Jennrich and Ralston, 1979). In either case, uncertainty can be expressed as a bivariate normal distribution for the model parameters.

Section F.1.3 discusses fixed parameters. Section F.1.4 describes, for each exposure factor, the EFH data used to develop the distributions, along with the final distributional statistics.

F.1.3 Fixed Parameters

Certain parameters were fixed, based on central tendency values from the best available source (usually EFH recommendations), either because no variability was expected or because the available data were not adequate to generate distributions. Fixed (constant) parameters are shown in Table F-2 along with the value selected for the risk analysis and the data source. These constants include variables for which limited or no percentile data were provided in the EFH: exposure frequency, fractions of T3 and T4 fish consumed, and fraction contaminated for the various media. Most of these values were extracted directly from the EFH. When evaluating carcinogens, total dose is averaged over the lifetime of the individual, assumed to be 70 years.

[1] Gamma, Weibull, and lognormal distributions are all special cases of the generalized gamma distribution.

Table F-2. Summary of Human Exposure Factor Data Used in Modeling: Constants

Description	Value	Units	Source
Fraction contaminated: drinking water	1	Fraction	EPA policy
Fraction contaminated: fish	1	Fraction	EPA policy
Fraction of T3 fish consumed	0.36	Fraction	U.S. EPA (1997b); Table 10-66
Fraction of T4 fish consumed	0.64	Fraction	U.S. EPA (1997b); Table 10-66
Exposure frequency (adult, child)	350	d/yr	EPA policy
Averaging time for carcinogens (adult, child)	70	yr	U.S. EPA (1989)

The fraction contaminated for drinking water was assumed to be 1 (i.e., all drinking water available for consumption at a site is potentially contaminated), with actual concentrations depending on fate and transport model results. Thus, households for which the drinking water pathway was analyzed were assumed to get 100 percent of their drinking water from groundwater. Exposure frequency was set to 350 days per year in accordance with EPA policy, assuming that residents take an average of 2 weeks' vacation time away from their homes each year.

F.1.4 Variable Parameters

F.1.4.1 Fish Consumption

Table F-3 presents fish consumption data and distributions. Fish consumption data were obtained from Table 10-64 of the EFH (U.S. EPA, 1997b). Data (in g/d) were available for adult freshwater anglers in Maine. The Maine fish consumption study was one of four recommended freshwater angler studies in the EFH (U.S. EPA, 1997b). The other recommended fish consumption studies (i.e., Michigan and New York) had large percentages of anglers who fished from Great Lakes, which is not consistent with the modeling scenarios used in this risk analysis. The anglers in the Maine study fished from streams, rivers, and ponds; these data are more consistent with our modeling scenarios. Although the Maine data have a lower mean than the Michigan data, the Maine data compared better with a national U.S. Department of Agriculture (USDA) study. Also, the Maine study included percentile data, which were necessary to develop a distribution.

Percentile data were used to fit parametric models (gamma, lognormal, and Weibull), and measures of goodness of fit were used to select lognormal as the most appropriate model. The fraction of fish intake that is locally caught was assumed to be 1 (in accordance with EPA policy). The fraction of consumed T3 and T4 fish was 0.36 and 0.64, respectively (Table 10-66, U.S. EPA, 1997b).

Table F-3. Fish Consumption Data and Distribution

EFH Data (g/d)									Distribution		
Age Cohort	N	Data Mean	Data SD	P50	P66	P75	P90	P95	Distribution	Pop-Estd Mean	Pop-Estd SD
All ages	1,053	6.4		2	4	5.8	13	26	Lognormal	6.48	19.9

N = Number of samples; P50–P95 = Percentiles; Pop-Estd = Population-estimated; SD = Standard deviation.

F.1.4.2 Drinking Water Intake

Table F-4 presents drinking water intake data and distributions. Drinking water intake data were obtained from Table 3-6 of the EFH (U.S. EPA, 1997a). Data (in mL/d) were presented by age groups. Weighted averages of percentiles, means, and standard deviations were calculated for the three child age groups and adults. Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model. The fraction of drinking water contaminated was assumed to be 1 (in accordance with EPA policy).

Table F-4. Drinking Water Intake Data and Distributions

EFH Data (mL/d)													Distributions		
Age Cohort	N	Data Mean	Data SD	P01	P05	P10	P25	P50	P75	P90	P95	P99	Distribution	Pop-Estd Mean	Pop-Estd SD
1–5	3,200	697.1	401.5	51.62	187.6	273.5	419.2	616.5	900.8	1,236	1,473	1,917	Gamma	698	406
6–11	2,405	787	417	68	241	318	484	731	1,016	1,338	1,556	1,998	Gamma	787	430
12–19	5,801	963.2	560.6	65.15	241.4	353.8	574.4	868.5	1,247	1,694	2,033	2,693	Gamma	965	574
20+	13,394	1,384	721.6	207.6	457.5	607.3	899.6	1,275	1,741	2,260	2,682	3,737	Gamma	1,383	703

N = Number of samples; P01–P99 = Percentiles; Pop-Estd = Population-estimated; SD = Standard deviation.

F.1.4.3 Body Weight

Table F-5 presents body weight data and distributions. Body weight data were obtained from Tables 7-2 through 7-7 of the EFH (U.S. EPA, 1997a). Data (in kg) were presented by age and gender. Weighted averages of percentiles, means, and standard deviations were calculated for 1- to 5-year-olds, 6- to 11-year-olds, 12- to 19-year olds, and adult age groups; male and female data were weighted and combined for each age group. These percentile data were used as the basis for fitting distributions. These data were analyzed to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model.

Table F-5. Body Weight Data and Distributions

EFH Data (kg)													Distributions		
Age Cohort	N	Data Mean	Data SD	P05	P10	P15	P25	P50	P75	P85	P90	P95	Distribution	Pop-Estd Mean	Pop-Estd SD
1–5	3,762	15.52	3.719	12.5	13.1	13.45	14.03	15.26	16.67	17.58	18.32	19.45	Lognormal	15.5	2.05
6–11	1,725	30.84	9.561	22.79	24.05	25.07	26.44	29.58	33.44	36.82	39.66	43.5	Lognormal	30.7	5.96
12–19	2,615	58.45	13.64	43.84	46.52	48.31	50.94	56.77	63.57	68.09	71.98	79.52	Lognormal	58.2	10.2
20+	12,504	71.41	15.45	52.86	55.98	58.21	61.69	69.26	78.49	84.92	89.75	97.64	Lognormal	71.2	13.3

N = Number of samples; P05–P95 = Percentiles; Pop-Estd = Population-estimated; SD = Standard deviation.

F.1.4.4 Exposure Duration

Table F-6 presents exposure duration data and distributions. Exposure duration was assumed to be equivalent to the average residence time for each receptor. Exposure durations for adult and child residents were determined using data on residential occupancy from the EFH Table 15-168 (U.S. EPA, 1997c). The data represent the total time a person is expected to live at a single location, based on age. The table presents male and female data combined. Adult residents aged 21 to 90 were pooled. For child residents, the 3-year-old age group was used for the 1- to 5-year-olds. The 6- and 9-year-old age groups were pooled for the 6- to 11-year-old cohort.

Table F-6. Exposure Duration Data and Distributions

EFH Data		Distributions		
Age Cohort	**Data Mean (yr)**	**Distribution**	**Pop-Estd Shape (yr)[a]**	**Pop-Estd Scale (yr)**
1–5	6.5	Weibull	1.32	7.059
6–11	8.5	Weibull	1.69	9.467
Adult	16.0	Weibull	1.34	17.38

Pop-Estd = Population-estimated.
[a] Distributions used in risk assessment.

In an analysis of residential occupancy data, Myers et al. (U.S. EPA, 2000) found that the data, for most ages, were best fit by a Weibull distribution. The Weibull distribution as implemented in Crystal Ball® is characterized by three parameters: location, shape, and scale. Location is the minimum value and, in this case, was presumed to be 0. Shape and scale were determined by fitting a Weibull distribution to the pooled data, as follows. To pool residential occupancy data for the age cohorts, an arithmetic mean of data means was calculated for each age group. Then, assuming a Weibull distribution, the variance within each age group (e.g., 6-year-olds) was calculated in the age cohort. These variances in turn were pooled over the age cohort using equal weights. This is not the usual type of pooled variance, which would exclude the variation in the group means. However, this way, the overall variance reflected the variance of means within the age groups (e.g., within the 6-year-old age group). The standard deviation was estimated as the square root of the variance. The coefficient of variation was calculated as the ratio of the standard deviation divided by the Weibull mean. For each cohort, the population-estimated parameter uncertainty information (e.g., shape and scale) was calculated based on a Weibull distribution, the calculated data mean for the age cohort, and the CV.

F.2 References

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U.S. EPA (Environmental Protection Agency). 2000. *Options for Development of Parametric Probability Distributions for Exposure Factors.* EPA/600/R-00/058. National Center for Environmental Assessment, Office of Research and Development, Washington, DC. July.

Appendix G. Human Health Benchmarks

The coal combustion waste (CCW) risk assessment will require human health benchmarks to assess potential risks from chronic oral and inhalation exposures. The U.S. Environmental Protection Agency (EPA) uses reference doses (RfDs) and reference concentrations (RfCs) to evaluate noncancer risk from oral and inhalation exposures, respectively. Oral cancer slope factors (CSFs), inhalation unit risk factors (URFs), and inhalation CSFs are used to evaluate risk for carcinogens.

This appendix provides the human health benchmarks used in the CCW screening and risk assessment. Section G.1 describes the data sources and general hierarchy used to collect these benchmarks. Section G.2 provides the benchmarks along with discussions of individual human health benchmarks extracted from a variety of sources.

G.1 Methodology and Data Sources

Several sources of health benchmarks are available. The hierarchy used health benchmarks developed by EPA to the extent that they were available. The analysis used available benchmarks from non-EPA sources for chemicals for which EPA benchmarks were not available, and ranked human health benchmark sources in the following order of preference:

- Integrated Risk Information System (IRIS)
- Superfund Technical Support Center Provisional Benchmarks
- Health Effects Assessment Summary Tables (HEAST)
- EPA health assessment documents
- Various other EPA health benchmark sources
- Agency for Toxic Substances and Disease Registry (ATSDR) minimal risk levels (MRLs)
- California Environmental Protection Agency (CalEPA) chronic inhalation reference exposure levels (RELs) and cancer potency factors.

G.1.1 Integrated Risk Information System (IRIS)

Benchmarks in IRIS are prepared and maintained by EPA, and RTI used values from IRIS whenever available. IRIS is EPA's electronic database containing information on human health effects (U.S. EPA, 2002). Each chemical file contains descriptive and quantitative information on potential health effects. Health benchmarks for chronic noncarcinogenic health

effects include RfDs and RfCs. Cancer classification, oral CSFs, and inhalation URFs are included for carcinogenic effects. IRIS is the official repository of Agency-wide consensus of human health risk information.

Inhalation CSFs are not available from IRIS, so we calculated them from inhalation URFs (which are available from IRIS) using the following equation:

$$inh\ CSF = inh\ URF \times 70\,kg \div 20\,m^3/d \times 1000\,\mu g/mg$$

In this equation, 70 kg represents average body weight; 20 m^3/d represents average inhalation rate; and 1000 µg/mg is a units conversion factor (U.S. EPA, 1997). EPA uses these standard estimates of body weight and inhalation rate in the calculation of the URF; therefore, we used these values to calculate inhalation CSFs.

G.1.2 Superfund Provisional Benchmarks

The Superfund Technical Support Center (EPA's National Center for Environmental Assessment [NCEA]) derives provisional RfCs, RfDs, and CSFs for certain chemicals. These provisional health benchmarks can be found in Risk Assessment Issue Papers. Some of the provisional values have been externally peer reviewed. These provisional values have not undergone EPA's formal review process for finalizing benchmarks and do not represent Agency-wide consensus information.

G.1.3 Health Effects Assessment Summary Tables

HEAST is a listing of provisional noncarcinogenic and carcinogenic health toxicity values (RfDs, RfCs, URFs, and CSFs) derived by EPA (U.S. EPA, 1997). Although the health toxicity values in HEAST have undergone review and have the concurrence of individual EPA program offices, either they have not been reviewed as extensively as those in IRIS or their data set is not complete enough to be listed in IRIS. HEAST benchmarks have not been updated in several years and do not represent Agency-wide consensus information.

G.1.4 Other EPA Health Benchmarks

EPA has also derived health benchmark values in other risk assessment documents, such as Health Assessment Documents (HADs), Health Effects Assessments (HEAs), Health and Environmental Effects Profiles (HEEPs), Health and Environmental Effects Documents (HEEDs), Drinking Water Criteria Documents, and Ambient Water Quality Criteria Documents. Evaluations of potential carcinogenicity of chemicals in support of reportable quantity adjustments were published by EPA's Carcinogen Assessment Group (CAG) and may include cancer potency factor estimates. Health benchmarks derived by EPA for listing determinations (e.g., solvents) or studies (e.g., Air Characteristic Study) are also available. Health toxicity values identified in these EPA documents are usually dated and are not recognized as Agency-wide consensus information or verified benchmarks.

G.1.5 ATSDR Minimal Risk Levels

The ATSDR MRLs are substance-specific health guidance levels for noncarcinogenic endpoints (ATSDR, 2002). An MRL is an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse noncancer health effects over a specified duration of exposure. MRLs are based on noncancer health effects only and are not based on a consideration of cancer effects. MRLs are derived for acute, intermediate, and chronic exposure durations for oral and inhalation routes of exposure. Inhalation and oral MRLs are derived in a manner similar to EPA's RfCs and RfDs, respectively (i.e., ATSDR uses the no observed adverse effect level/uncertainty factor [NOAEL/UF] approach); however, MRLs are intended to serve as screening levels and are exposure duration specific. Also, ATSDR uses EPA's (U.S. EPA, 1994) inhalation dosimetry methodology in the derivation of inhalation MRLs.

G.1.6 CalEPA Cancer Potency Factors and Reference Exposure Levels

CalEPA has developed cancer potency factors for chemicals regulated under California's Hot Spots Air Toxics Program (CalEPA, 1999a). The cancer potency factors are analogous to EPA's oral and inhalation CSFs. CalEPA has also developed chronic inhalation RELs, analogous to EPA's RfC, for 120 substances (CalEPA, 1999b, 2000). CalEPA used EPA's (U.S. EPA, 1994) inhalation dosimetry methodology in the derivation of inhalation RELs. The cancer potency factors and inhalation RELs have undergone internal peer review by various California agencies and have been the subject of public comment.

G.1.7 Surrogate Health Benchmarks

If no human health benchmarks were available from EPA or alternative sources, we sought benchmarks for similar chemicals to use as surrogate data. For example, the health benchmark of a mixture could serve as the surrogate benchmark for its components or a benchmark of a metal salt could serve as the surrogate for an elemental metal.

G.2 Human Health Benchmarks

The chronic human health benchmarks used to calculate the health-based numbers (HBNs) in the CCW risk assessment are summarized in Table G-1, which provides the Chemical Abstract Service Registry Number (CASRN), constituent name, RfD (mg/kg-d), RfC (mg/m^3), oral CSF (mg/kg-d^{-1}), inhalation URF [(µg/m^3)$^{-1}$], inhalation CSF (mg/kg-d^{-1}), and reference for each benchmark. A key to the references cited and abbreviations used is provided at the end of the table.

For a majority of constituents, human health benchmarks were available from IRIS (U.S. EPA, 2002), Superfund Provisional Benchmarks, or HEAST (U.S. EPA, 1997). Benchmarks also were obtained from ATSDR (2002) or CalEPA (1999a, 1999b, 2000). This section describes benchmarks obtained from other sources, along with the Superfund Provisional Benchmarks values and special uses of IRIS benchmarks.

Provisional inhalation health benchmarks were developed in the Air Characteristic Study (U.S. EPA, 1999) for several constituents lacking IRIS, HEAST, alternative EPA, or ATSDR

values. For vanadium, the study on which the ATSDR acute inhalation MRL is based was used but was adjusted for chronic exposure. Additional details on the derivation of this inhalation benchmark can be found in the *Revised Risk Assessment for the Air Characteristic Study* (U.S. EPA, 1999).

The provisional RfD of 0.02 mg/kg-d developed by NCEA for the Superfund Technical Support Center (U.S. EPA, 2001a) was used for cobalt.

Table G-1. Human Health Benchmarks Used in CCW Risk Assessment

Constituent Name	CASRN	RfD (mg/kg-d)	Ref	RfC (mg/m^3)	Ref	CSFo (per mg/kg-d)	Ref	URF (per µg/m3)	Ref	CSFi (per mg/kg-d)	Ref	MCL (mg/L)	Notes
Aluminum	7429-90-5	2.0E+00	A										RfD is for intermediate duration
Ammonia	7664-41-7	9.7E-01	H	1.0E-01	I								RfD= 34 mg/L
Antimony	7440-36-0	4.0E-04	I	2.0E-04	I								RfC is for antimony trioxide
Arsenic, inorganic	7440-38-2	3.0E-04	I	3.0E-05	Cal00	1.5E+0	I	4.3E-3	I	1.5E+1	calc		
Barium	7440-39-3	7.0E-02	I	5.0E-04	H								
Beryllium	7440-41-7	2.0E-03	I	2.0E-05	I			2.4E-3	I	8.4E+0	calc		
Boron	7440-42-8	9.0E-02	I	2.0E-02	H								
Cadmium	7440-43-9	5.0E-04	I	2.0E-05	Cal00			1.8E-3	I	6.3E+0	calc		RfD for H_2O (food = 1E-3)
Chloride	16887-00-6											250	
Chromium (III), insoluble salts	16065-83-1	1.5E+00	I										
Chromium (VI)	18540-29-9	3.0E-03	I	1.0E-04	I			1.2E-2	I	4.2E+1	calc		
Cobalt (and compounds)	7440-48-4	2.0E-02	SF	1.0E-04	A			2.8E-3	SF	9.8E+0	calc		
Copper	7440-50-8											1.3	
Cyanide (amenable)	57-12-5	2.0E-02	I										
Divalent mercury		3.0E-04	H										RfD is for mercuric chloride; used for food, water, soil
Divalent mercury		1.0E-04	I										RfD is for methyl mercury; used for fish only
Fluoride	16984-48-8	1.2E-01	I										RfD is for fluorine; the alternative IRIS value (for skeletal, rather than dental, fluorosis) was used
Iron	7439-89-6											0.3	
Lead and compounds (inorganic)	7439-92-1											0.015	
Manganese	7439-96-5	1.4E-01	I	5.0E-05	I								RfD for food; H_2O and soil = 4.7E-2 mkd
Molybdenum	7439-98-7	5.0E-03	I										

(continued)

Table G-1. (continued)

Constituent Name	CASRN	RfD (mg/kg-d)	Ref	RfC (mg/m^3)	Ref	CSFo (per mg/kg-d)	Ref	URF (per µg/m3)	Ref	CSFi (per mg/kg-d)	Ref	MCL (mg/L)	Notes
Nickel, soluble salts	7440-02-0	2.0E-02	I	2.0E-04	A								
Nitrate	14797-55-8	1.6E+00	I									10	
Nitrite	14797-65-0	1.0E-01	I										
Selenium	7782-49-2	5.0E-03	I	2.0E-02	Cal00								
Silver	7440-22-4	5.0E-03	I										
Strontium	7440-24-6	6.0E-01	I										
Sulfate	14808-79-8											250	
Thallium, elemental	7440-28-0	8.0E-05	I										RfD is for thallium chloride
Total dissolved solids												500	
Vanadium	7440-62-2	7.0E-03	H	7.0E-05	AC								
Zinc	7440-66-6	3.0E-01	I										

Key:
CASRN = Chemical Abstract Service registry number.
RfD = Reference dose.
RfC = Reference concentration.
MCL = Maximum contaminant level.
CSFo = Oral cancer slope factor.
CSFi = Inhalation cancer slope factor.
URF = Unit risk factor.

[a] Sources:
A = ATSDR MRLs (ATSDR, 2002)
AC = Developed for the Air Characteristic Study (U.S. EPA, 1999)
calc = Calculated
Cal00 = CalEPA chronic REL (CalEPA, 2000)
H = HEAST (U.S. EPA, 1997)
I = IRIS (U.S. EPA, 2002)
SF = Superfund Risk Issue Paper (U.S. EPA, 2001a,b)

For several constituents, IRIS benchmarks for similar chemicals were used as surrogate data. The rationale for these recommendations is as follows:

- The RfC for antimony trioxide (2E-04 mg/m^3) was used as a surrogate for antimony.
- Fluoride was based on fluorine. The IRIS RfD for fluorine is based on soluble fluoride. The primary RfD cited in IRIS (6E-02 mg/kg-d) is for dental fluorosis, a cosmetic effect. In this analysis, an alternative IRIS value (1.2E-01 mg/kg-d) for skeletal fluorosis in adults was used instead.
- The RfC for mercuric chloride (9E-05 mg/m^3) was used as a surrogate for elemental mercury. The RfDs for mercuric chloride (3E-04 mg/kg-d) and methyl mercury (1E-04 mg/kg-d) were used as surrogates for elemental mercury for assessing potential risks from food, soil, and water ingestion, and fish ingestion, respectively.
- Thallium was based on thallium chloride. There are several thallium salts that have RfDs in IRIS. The lowest value among the thallium salts (8E-05 mg/kg-d) is routinely used to represent thallium in risk assessments.

G.3 References

ATSDR (Agency for Toxic Substances and Disease Registry). 2002. *Minimal Risk Levels (MRLs) for Hazardous Substances.* Available: http://www.atsdr.cdc.gov/mrls.html

CalEPA (California Environmental Protection Agency). 1999a. *Air Toxics Hot Spots Program Risk Assessment Guidelines: Part II. Technical Support Document for Describing Available Cancer Potency Factors*. Office of Environmental Health Hazard Assessment, Berkeley, CA. Available: http://www.oehha.org/air/cancer_guide/hsca2.html

CalEPA (California Environmental Protection Agency). 1999b. *Air Toxics Hot Spots Program Risk Assessment Guidelines: Part III. Technical Support Document for the Determination of Noncancer Chronic Reference Exposure Levels*. SRP Draft. Office of Environmental Health Hazard Assessment, Berkeley, CA. Available (in two sections): http://www.oehha.org/air/chronic_rels/ragsii.html, http://www.oehha.org/air/chronic_rels/RAGSp3draft.html.

CalEPA (California Environmental Protection Agency). 2000. *Air Toxics Hot Spots Program Risk Assessment Guidelines: Part III. Technical Support Document for the Determination of Noncancer Chronic Reference Exposure Levels*. Office of Environmental Health Hazard Assessment, Berkeley, CA. Available (in four sections):
http://www.oehha.org/air/chronic_rels/22RELS2k.html
http://www.oehha.org/air/chronic_rels/42kChREL.html
http://www.oehha.org/air/chronic_rels/Jan2001ChREL.html
http://www.oehha.org/air/chronic_rels/1201Crels.html

U.S. EPA (Environmental Protection Agency). 1994. *Methods for Derivation of Inhalation Reference Concentrations and Application of Inhalation Dosimetry*. EPA/600/8-90-066F.

Environmental Criteria and Assessment Office, Office of Health and Environmental Assessment, Office of Research and Development, Research Triangle Park, NC.

U.S. EPA (Environmental Protection Agency). 1997. *Health Effects Assessment Summary Tables (HEAST)*. EPA-540-R-97-036. FY 1997 Update. Office of Solid Waste and Emergency Response, Washington, DC.

U.S. EPA (Environmental Protection Agency). 1999. *Revised Risk Assessment for the Air Characteristic Study*. EPA-530-R-99-019a. Volume 2. Office of Solid Waste, Washington, DC.

U.S. EPA (Environmental Protection Agency). 2001a. *Risk Assessment Paper for Derivation of a Provisional RfD for Cobalt and Compounds (CASRN 7440-48-4).* 00-122/3-16-01. National Center for Environmental Assessment. Superfund Technical Support Center, Cincinnati, OH.

U.S. EPA (Environmental Protection Agency). 2001b. *Risk Assessment Paper for Derivation of a Provisional Carcinogenicity Assessment for Cobalt and Compounds (CASRN 7740-48-4).* 00-122/3-16-01. National Center for Environmental Assessment. Superfund Technical Support Center, Cincinnati, OH.

U.S. EPA (Environmental Protection Agency). 2002. Integrated Risk Information System (IRIS). National Center for Environmental Assessment, Office of Research and Development, Washington, DC. Available: http://www.epa.gov/iris/

Appendix H. Ecological Benchmarks

Both the screening and full-scale CCW assessments include an ecological risk assessment that parallels the human health risk assessment. The ecological risk assessment addresses two routes of exposure for ecological receptors: direct contact with contaminated media and ingestion of contaminated food items. For each CCW chemical for which ecological effect data were available, hazard quotients (HQs) were calculated using chemical-specific media concentrations assumed to be protective of ecological receptors of concern.

This appendix provides the ecological benchmarks used in both the CCW screening and full-scale risk assessment. Section H.1 describes the data sources and methods used to develop these benchmarks. Additional details can be found in U.S. EPA (1998). Section H.2 provides the benchmarks.

H.1 Data Sources and Methodology

To calculate ecological HQs, the concentration-based ecological benchmarks (also known as chemical stressor concentration limits, or CSCLs) were divided by the estimated concentrations of constituents in environmental media contaminated by CCW. The CSCLs are environmental quality criteria intended to represent a protective threshold value for adverse effects to various ecological receptors in terrestrial (soil) and aquatic ecosystems (surface water and sediment). An HQ greater than target of 1 indicates that the predicted concentration will be above the CSCL and, therefore, the potential for adverse ecological effects exists. In this regard, the use of CSCLs to calculate an ecological HQ is analogous to the use of the reference concentration (RfC) for human health where the air concentration is compared to the health-based concentration (the RfC), and an HQ greater than the target value of 1 is considered to indicate the potential for adverse health effects. Table H-1 shows the receptor types assessed for each exposure route in each environmental medium addressed by the CCW risk assessment.

Table H-1. Ecological Receptors Assessed by Medium Impacted by CCW

Receptor Type	Surface Water	Sediment	Soil
Direct Contact Exposure			
Aquatic Community	✔		
Sediment Community		✔	
Soil Community			✔
Amphibians	✔		
Aquatic Plants and Algae	✔		
Terrestrial Plants			✔
Ingestion Exposure			
Mammals	✔		✔
Birds	✔		✔

Ecological benchmarks for the CCW risk assessment were taken directly from the 1998 fossil fuel combustion risk analysis, *Non-Groundwater Pathways, Human Health and Ecological Risk Analysis for Fossil Fuel Combustion Phase 2 (FFC2)* (U.S. EPA, 1998). The receptors and endpoints selected for the 1998 analysis were evaluated and considered appropriate for the goals of this risk assessment. The benchmarks were derived for each chemical and receptor to the extent that supporting data were available.

As in 1998, the lowest (most sensitive) benchmark for each chemical in each medium was selected to calculate HQs in the CCW risk assessment. For example, several receptors (soil invertebrates, terrestrial plants, mammals, and birds) are exposed to constituents in soils. The soil HQ for a given chemical was calculated using whichever soil benchmark was lowest and would thus give the highest (most conservative) HQ.

H.1.1 Direct Contact Exposure

Ecological receptors that live in close contact with contaminated media are considered to be potentially at risk. These receptors are exposed through direct contact with contaminants in surface water, sediment, and soil. The receptors selected to assess the direct contact exposure route for each medium were previously summarized in Table H-1. The benchmarks for receptor communities are not truly *community-level* concentration limits in that they do not consider predator-prey interactions. Rather, they are based on the theory that protection of 95 percent of the species in the community will provide a sufficient level of protection for the community (see, for example, Stephan et al., 1985, for additional detail). The following sections summarize the benchmark derivation methods for each receptor assessed for the direct contact route of exposure.

Aquatic Community Benchmarks

The aquatic community receptor comprises fish and aquatic invertebrates exposed through direct contact with constituents in surface water. For the aquatic community, the final chronic value (FCV), developed either for the Great Lakes Water Quality Initiative (U.S. EPA, 1993) or the National Ambient Water Quality Criteria (NAWQC) (U.S. EPA, 1995a,b), was the preferred source for the benchmark. If an FCV was unavailable and could not be calculated from available data, a secondary chronic value (SCV) was estimated using methods developed for wildlife criteria for the Great Lakes Initiative (e.g., 58 FR 20802; U.S. EPA, 1993). The SCV methodology is based on the original species data set established for the NAWQC; however, it requires fewer data points and includes statistically derived adjustment factors. For benchmark derivation, the minimum data set required at least one data point.

Amphibian Benchmarks

For amphibian populations, data availability severely limited benchmark development. A review of several compendia presenting amphibian ecotoxicity data (e.g., U.S. EPA, 1996; Power et al., 1989), as well as primary literature sources, found a lack of standard methods on endpoints, species, and test durations necessary to derive a chronic benchmark for amphibians. Consequently, an acute benchmark was derived for aqueous exposures in amphibians by taking a geometric mean of LC_{50} (i.e., concentration lethal to 50 percent of test subjects) data identified in studies with exposure durations less than 8 days. Although the use of acute effects levels is not

consistent with other benchmarks, the sensitivity of these receptors warrants their use in lieu of chronic concentration limits. Recent studies (Hopkins and Rowe, 2004; Hopkins et al., 2006) have confirmed that amphibians are among the most sensitive taxa to metals found in CCW, and selenium appears to be a significant stressor in CCW disposal scenarios. The endpoints considered in these studies were related to population sustainability and, consequently, are highly relevant to ecological risk assessment. However, these field studies are confounded by the fact that wildlife were exposed to multiple chemical pollutants (including radionuclides) and, as a result, acute effects data on individual metals remain the most appropriate source for quantitative benchmarks to assess the potential for adverse effects in amphibians.

Sediment Community Benchmarks

For the sediment community, benchmarks were selected based on a complete assessment of several sources proposing sediment benchmark values. Primary sources evaluated for developing sediment community benchmarks are shown in Table H-2.

Table H-2. Primary Sources Evaluated for Developing Sediment Community Benchmarks

Long, E.R., and L.G. Morgan. 1991. *The Potential for Biological Effects of Sediment-Sorbed Contaminants Tested in the National Status and Trends Program*. Technical Memorandum NOS OMA 52. National Oceanic and Atmospheric Administration (NOAA), Washington, DC.
Jones, D.S., G.W. Suter, II, and R.N. Hull. 1997. *Toxicological Benchmarks for Screening Contaminants of Potential Concern for Effects on Sediment-Associated Biota: 1997 Revision*. Oak Ridge National Laboratory, Oak Ridge, TN.
U.S. EPA (Environmental Protection Agency). 1997. *Protocol for Screening Level Ecological Risk Assessment at Hazardous Waste Combustion Facilities*. Internal Review Draft, February 28. Office of Solid Waste, Washington, DC.
U.S. EPA (Environmental Protection Agency). 1995. *Technical Support Document for the Hazardous Waste Identification Rule: Risk Assessment for Human and Ecological Receptors*. Office of Solid Waste, Washington, DC.
MacDonald, D.D. 1994. *Approach to the Assessment of Sediment Quality in Florida Coastal Waters. Volume 1*. Florida Department of Environmental Protection, Tallahassee, FL.

Soil Community Benchmarks

For the soil community, the preferred methods for deriving benchmarks are analogous to those used in deriving the NAWQC. Benchmark values for soil fauna were estimated to protect 95 percent of the species found in a typical soil community, including earthworms, insects, and various other soil fauna. The methodology presumes that protecting 95 percent of the soil species with a 50th percentile level of confidence will ensure long-term sustainability of a functioning soil community. The toxicity data on soil fauna were taken from several major compendia and supplemented with additional studies identified in the open literature.

The approach to calculating benchmarks for the soil community is based on efforts by Dutch scientists (i.e., the Netherlands' National Institute of Public Health and Environmental Protection [RIVM] methodology) to develop hazardous concentrations (HCs) at specified levels

of protection (primarily 95 percent) at both a 95th percentile and a 50th percentile level of confidence (Sloof, 1992). For the soil fauna benchmarks, the 50th percentile level of confidence was selected because the 95th percentile appeared to be overly conservative for a "no effects" approach. The RIVM methodology follows two steps: (1) fitting a distribution to the log of the selected endpoints, and (2) extrapolating to a benchmark concentration based on the mean and standard deviation of a set of endpoints. The key assumptions in the Dutch methodology are that (1) lowest observed effects concentration (LOEC) data are distributed logistically, and (2) the 95 percent level of protection is ecologically significant. The following formula was used to calculate soil fauna benchmarks:

$$HC_{5\%} = \left[x_m - k_1 s_m\right] \qquad \text{(H-1)}$$

where

$HC_{5\%}$ = soil concentration protecting 95 percent of the soil species
x_m = sample mean of the log LOEC data
k_l = extrapolation constant for calculating the one-sided leftmost confidence limit for a 95 percent protection level
s_m = sample standard deviation of the log LOEC data.

Sufficient data were available to develop benchmarks using this methodology for four of the metals of concern: cadmium, copper, lead, and zinc. For the remaining constituents, benchmark studies identifying effects to earthworms and other soil biota proposed by Oak Ridge National Laboratory (Efroymson et al., 1997a) or criteria developed by the Canadian Council of Ministers of the Environment (CCME, 1997) were used to estimate protective soil concentrations.

Algae and Aquatic Plant Benchmarks

For algae and aquatic plants, adverse effects concentrations are identified in the open literature or from a data compilation presented in *Toxicological Benchmarks for Screening Potential Contaminants of Concern for Effects on Aquatic Biota: 1996 Revision* (Suter and Tsao, 1996). For most contaminants, studies were not available for aquatic vascular plants, and lowest effects concentrations were identified for algae. The benchmark for algae and aquatic plants was based on (1) an LOEC for vascular aquatic plants or (2) an effective concentration (EC_{xx}) for a species of freshwater algae, frequently a species of green algae (e.g., *Selenastrum capricornutum*). Because of the lack of data for this receptor group and the differences between vascular aquatic plants and algae sensitivity, the lowest value of those identified was usually chosen.

Terrestrial Plant Benchmarks

For the terrestrial plant community, ecotoxicological data were identified from a summary document prepared at the Oak Ridge National Laboratory: *Toxicological Benchmarks for Screening Contaminants of Potential Concern for Effects on Terrestrial Plants: 1997 Revision* (Efroymson et al., 1997b). The measurement endpoints are generally limited to growth and yield parameters because (1) they are the most common class of response reported in phytotoxicity studies and, therefore, will allow for criterion calculations for a large number of

constituents, and (2) they are ecologically significant responses both in terms of plant populations and, by extension, the ability of producers to support higher trophic levels. As presented in Efroymson et al. (1997a), benchmarks for phytotoxicity were selected by rank ordering the LOEC values and then approximating the 10th percentile. If there were 10 or fewer values for a chemical, the lowest LOEC was used. If there were more than 10 values, the 10th percentile LOEC was used.

H.1.2 Ingestion Exposure

The ingestion route of exposure addresses the exposure of terrestrial mammals and birds through ingestion of plants and prey and incidental soil ingestion. Thus, the CCW ecological benchmarks for ingestion exposure express media concentrations that, based on certain assumptions about receptor diet and foraging behavior, are expected to be protective of populations of mammals and birds feeding and foraging in contaminated areas.

The derivation of ingestion benchmarks begins with the selection of appropriate ecotoxicological data based on a hierarchy of data sources. The assessment endpoint for the CCW ecological risk assessment is population viability; therefore, ecological benchmarks were developed from measures of reproductive/developmental success or, if unavailable, from other effects that could conceivably impair population dynamics. Population-level benchmarks are preferred over benchmarks for individual organisms; however, very few population-level benchmarks have been developed. Therefore, the CCW risk assessment uses benchmarks derived from individual organism studies, and protection is inferred at the population level.

Once an appropriate ingestion exposure study was identified, a benchmark was calculated using a three-step process. The remainder of this section outlines the basic technical approach used to convert avian or mammalian benchmarks (in daily doses) to the media concentration benchmarks (in units of concentration) used to assess ecological risks for surface water and soil contaminated by CCW waste constituents. The methods reflect exposure through the ingestion of contaminated plants, prey, and various media, and include parameters on accumulation (e.g., bioconcentration factors), uptake (e.g., consumption rates), and dietary preferences.

Step 1: Scale Benchmark

The benchmarks derived for test species can be extrapolated to wildlife receptor species within the same taxon using a cross-species scaling equation (Equation H-2) (Sample et al., 1996). This is the default methodology EPA proposed for carcinogenicity assessments and reportable quantity documents for adjusting animal data to an equivalent human dose (57 FR 24152).

$$Benchmark_w = LOAEL_t \times \left(\frac{bw_t}{bw_w}\right)^{1/4} \qquad \text{(H-2)}$$

where

$Benchmark_w$ = scaled ecological benchmark for species *w* (mg/kg/d)
$LOAEL_t$ = lowest observed adverse effects level for test species (mg/kg/d)
bw_t = body weight of the surrogate test species (kg)
bw_w = body weight of the representative wildlife species (kg).

Step 2: Identify Bioconcentration Factors / Bioaccumulation Factors

For metal constituents, whole-body bioconcentration factors (BCFs) and bioaccumulation factors (BAFs) were identified for aquatic and terrestrial organisms that may be used as food sources (e.g., fish, plants, earthworms). The Oak Ridge National Laboratory has proposed methods and data that are useful in predicting bioaccumulation in earthworms and small mammals (Sample et al. 1998a,b). These values were typically identified in the open literature and EPA references.

Step 3: Calculate Benchmarks

The following equation provides the basis for calculating surface water benchmarks using a population-inference benchmark (e.g., endpoint on fecundity).

$$Benchmark = \frac{\left[I_{fish} \times \left(BAF \quad C_w\right)\right] + \left(I_w \times C_w\right)}{bw} \tag{H-3}$$

where

I_{fish}	=	intake of contaminated fish (kg/d)
BAF	=	whole-body bioaccumulation factor (L/kg)
bw	=	weight of the representative species (kg)
I_w	=	intake of contaminated water (L/d)
C_w	=	total concentration in the water (mg/L).

For chemicals that bioaccumulate significantly in fish tissue, the ingestion of contaminated food will tend to dominate the exposure (i.e., $[I_{fish} \times C_{fish}] >> [I_w\ C_w]$), and the water term (i.e., $[I_w \times C_w]$) can be dropped from Equation H-3, resulting in Equation H-4:

$$Benchmark = \frac{I_{fish} \times \left(BAF \times C_w\right)}{bw} \tag{H-4}$$

At the benchmark dose (mg/kg/d), the concentration in water is equivalent to the chemical stressor concentration limit for that receptor as a function of body weight, ingestion rate, and the bioaccumulation potential for the chemical of concern. Hence, Equation H-4 can be rewritten to solve for the surface water ($CSCL_{sw}$) as follows:

$$CSCL_{sw} = \frac{benchmark \times bw}{I_w + \left(I_{fish} \times BAF\right)} \tag{H-5}$$

For wildlife populations of mammals and birds in terrestrial systems, the soil benchmark ($CSCL_{soil}$) for a given receptor was calculated using Equation H-6:

$$CSCL_{soil} = \frac{benchmark \times bw}{I_{food} \sum \left(BCF_j \times F_j \times AB_j\right) + I_{soil}} \tag{H-6}$$

where

bw	=	body weight (kg)
I_{food}	=	total daily food intake of species (kg/d)
I_{soil}	=	total daily soil intake of species (kg/d)
BCF_j	=	bioaccumulation factor in food item *j* (assumed unitless)
F_j	=	fraction of diet consisting of food item *j* (unitless)
AB_j	=	absorption of chemical in the gut from food item *j*.

H.2 Ecological Benchmarks

The ecological benchmarks used to calculate ecological HQs in the CCW risk assessment are summarized in Table H-3, which provides the constituent name; the criterion and receptor for soil, sediment, and aquatic receptors; and the source for each benchmark.

Table H-3. Ecological Benchmarks Used in the CCW Risk Assessment

Constituent	Soil Criterion (mg/kg)	Terrestrial Receptor	Sediment Criterion (mg/kg)	Sediment Receptor	Aquatic Criterion (mg/L)	Aquatic Receptor	Source
Aluminum	ID	--	ID	--	0.09	Aquatic Biota	U.S. EPA (1998)
Antimony	14	Raccoon	2	Sediment biota	0.03	Aquatic Biota	U.S. EPA (1998)
Arsenic total	10	Plants	0.51	Spotted sandpiper	ID	--	U.S. EPA (1998)
Arsenic III	ID	--	ID	--	0.15	Aquatic Biota	U.S. EPA (1998)
Arsenic IV	ID	--	ID	--	8.10E-03	Aquatic Biota	U.S. EPA (1998)
Barium	500	Plants	190	Spotted sandpiper	4.00E-03	Aquatic Biota	U.S. EPA (1998)
Beryllium	ID	--	ID	--	6.60E-04	Aquatic Biota	U.S. EPA (1998)
Boron	0.5	Plants	ID	--	1.60E-03	Aquatic Biota	U.S. EPA (1998)
Cadmium	1	Soil invertebrates	0.68	Sediment biota	2.50E-03	Aquatic Biota	U.S. EPA (1998)
Chromium total	64	Soil invertebrates	16.63	Spotted sandpiper	ID	--	U.S. EPA (1998)
Chromium IV	ID	--	ID	--	0.09	Aquatic Biota	U.S. EPA (1998)
Chromium VI	ID	--	ID	--	0.01	Aquatic Biota	U.S. EPA (1998)
Cobalt	1000	Soil invertebrates	ID	--	0.02	Aquatic Biota	U.S. EPA (1998)
Copper	21	Soil invertebrates	18.7	Sediment biota	9.30E-03	Aquatic Biota	U.S. EPA (1998)
Lead	28	Soil invertebrates	0.22	Spotted sandpiper	3.00E-04	River Otter	U.S. EPA (1998)
Mercury	0.1	Soil invertebrates	0.11	Spotted sandpiper	1.90E-07	Kingfisher	U.S. EPA (1998)
Molybdenum	42.08	Amer. woodcock	34	Spotted sandpiper	0.37	Aquatic Biota	U.S. EPA (1998)
Nickel	30	Plants	15.9	Sediment biota	0.05	Aquatic Biota	U.S. EPA (1998)
Selenium total	1	Plants	ID	--	5.00E-03	Aquatic Biota	U.S. EPA (1998)
Selenium IV	ID	--	ID	--	0.03	Aquatic Biota	U.S. EPA (1998)

(continued)

Table H-3. (continued)

Constituent	Soil Criterion (mg/kg)	Terrestrial Receptor	Sediment Criterion (mg/kg)	Sediment Receptor	Aquatic Criterion (mg/L)	Aquatic Receptor	Source
Selenium VI	ID	--	ID	--	9.50E-03	Aquatic Biota	U.S. EPA (1998)
Silver	ID	--	0.73	Sediment biota	3.60E-04	Aquatic Biota	U.S. EPA (1998)
Thallium	ID	--	ID	--	0.01	Aquatic Biota	U.S. EPA (1998)
Vanadium	130.00	Soil invertebrates	18	Spotted sandpiper	0.02	Aquatic Biota	U.S. EPA (1998)
Zinc	50	Plants	120	Sediment biota	0.12	Aquatic Biota	U.S. EPA (1998)

ID = insufficient data.

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Glossary

AALG	ambient air level goal
AC	activated carbon
AECDP	Advanced Emissions Control Development Program (Babcock & Wilcox)
AFBC	atmospheric fluidized-bed combustor
APCD	air pollution control device
ACGIH	American Conference of Government Industrial Hygienists
ARD	Acid Rain Division (EPA)
ATSDR	Agency for Toxic Substances and Disease Registry
BAF	bioaccumulation factor
BAP	benzo[a]pyrene
BBF	biased burner firing
BCF	bioconcentration factor
BFB	bubbling fluidized bed
BOO	burners out of service
BSAF	biota sediment accumulation factor
CAA	Clean Air Act
CAP	Clean Air Act Assessment Package
CAPCOA	California Air Pollution Control Officers Association
CARB	California Air Resource Board
CCT	clean coal technology
CEDF	Clean Environment Development Facility (Babcock & Wilcox)
CFB	circulating fluidized bed
CLD	certainly lethal dose
CNS	central nervous system
CSF	cancer slope factor
DNA	deoxyribonucleic acid
DOC	dissolved organic carbon
DOE	Department of Energy
DSM	demand side management
E	(ratio of) exposure
ECTC	Environmental Control Test Center (EPRI)

EEI	Edison Electric Institute
EFP	emission factor program
EIA	Energy Information Administration (DOE)
E-LIDS™	Enhanced Limestone Injection Dry Scrubbing
EMF	emission modification factor
ENAMAP	Eastern North American Model of Air Pollution
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	electrostatic precipitator
EURMAP	European Regional Model of Air Pollution
FBC	fluidized-bed combustor
FCEM	field chemical emissions monitoring
FETC	Federal Energy Technology Center
FF	fabric filter
FGD	flue gas desulfurization
FGR	fluidized gas recirculation
FTIR	Fourier transform infrared
GEIA	Global Emissions Inventory Activity
GI	gastrointestinal
GIS	Geographic Information System
HAP	hazardous air pollutant
HEC	human equivalent concentration
HEM	Human Exposure Model
HI	hazard index
HQ	hazard quotient
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
IDLH	immediately dangerous to life and health
IEM	indirect exposure methodology
IGCC	integrated gasification combined cycle
IPP	independent power producer
IRIS	Integrated Risk Information System
IRP	Inerts Ranking Program
ISC3	Industrial Source Complex Version 3
ISCLT2	Industrial Source Complex Long Term Version 2

ISCLT3	Industrial Source Complex Long Term Version 3
ISCST3	Industrial Source Complex Short Term Version 3
IURE	inhalation unit risk estimate
LADD	lifetime averaged daily dose
LC_{50}/LD_{50}	lethal concentration/dose that kills 50% of test animals
LCUB	large coal-fired utility boiler
LET	linear energy transfer
L/G	liquid-to-gas
LOAEL	lowest-observed-adverse-effect level
LRT	long-range transport
MACT	maximum achievable control technology
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
MCUB	medium coal-fired utility boiler
MDL	minimum detectable level
MEI	maximally exposed individual
MFP	monofluorophosphate
MIR	maximum individual risk
MLE	maximum likelihood estimate
MRL	minimal risk level
MWC	municipal waste combustor
MWe	megawatts electric
MWI	medical waste incinerator
NAAQS	national ambient air quality standards
NAPAP	National Acid Precipitation Assessment Program
NAREL	National Air and Radiation Environmental Laboratory
NAS	National Academy of Science
NASN	National Air Surveillance Network
NGM	nested grid model
NIEHS	National Institute of Environmental Health Sciences
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NMHC	nonmethane hydrocarbon
NOAA	National Oceanographic and Atmospheric Administration
NOAEL	no-observed-adverse-effect level

NOEC	no-observed-effect concentration
NRC	National Research Council
NSPC	Northern States Power Company
NSPS	new source performance standards
NTP	National Toxicology Program
NWS	National Weather Service
OAQPS	Office of Air Quality Planning and Standards (EPA)
OAR	Office of Air and Radiation (EPA)
OFA	overfire air
ORD	Office of Research and Development (EPA)
ORIA	Office of Radiation and Indoor Air (EPA)
OSF	off-stoichiometric firing
OSHA	Occupational Safety and Health Administration
OTAG	Ozone Transport Assessment Group
OURE	oral unit risk estimate
PAB	Pollutant Assessment Branch (EPA)
PAH	polycyclic aromatic hydrocarbon
PBPK	physiologically based pharmacokinetic
PCB	polycyclic biphenyl
PCDD	polychlorinated dibenzo-p-dioxin
PCDF	polychlorinated dibenzofuran
PEL	permissible exposure limit
PFBC	pressurized fluidized-bed combustor
PM	particulate matter
PSCCo	Public Services Company of Colorado
PURPA	Public Utility Regulatory Policies Act
RAC	Risk Assessment Council (EPA)
RBC	risk based concentration
RCRA	Resource Conservation and Recovery Act
REL	reference exposure level
RELMAP	Regional Lagrangian Model of Air Pollution
RfC	reference concentration
RfD	reference dose
SAB	Science Advisory Board
SAMSON	Solar and Meteorological Surface Observation Network

SBS	small boiler simulator
SCR	selective catalytic reduction
SCRAM-BBS	Support Center for Regulatory Air Models Bulletin Board System
SCUB	small coal-fired utility boiler
SDA	spray dryer absorber
SE	standard error
SGU	steam generating unit
SIP	State Implementation Plan
SNCR	selective noncatalytic reduction
SPC	Science Policy Council (EPA)
STAR	STability ARray
TCDD	tetrachlorodibenzo-p-dioxin
TE	trace element
TEF	toxicity (or toxic) equivalency factor
TEQ	toxicity equivalent
TLV	threshold limit value
TOC	total organic compounds
tpy	tons per year
TRI	Toxics Release Inventory
TSP	total suspended particulate
TTN	Technology Transfer Network
UARG	Utility Air Regulatory Group
UDI	Utility Data Institute
UNDEERC	University of North Dakota Energy and Environmental Research Center
URE	unit risk estimate
USGS	U.S. Geological Survey
USPHS	U.S. Public Health Service
VOC	volatile organic compound
WHO	World Health Organization
WL	working level
WLM	working level month
WOE	weight of evidence

EXECUTIVE SUMMARY

ES.1 LEGISLATIVE MANDATE

In section 112(n)(1)(A) of the Clean Air Act, as amended (the Act), Congress directs the United States Environmental Protection Agency (EPA) to:

> "... perform a study of the hazards to public health reasonably anticipated to occur as a result of emissions by electric utility steam generating units of ... [hazardous air pollutants] ... after imposition of the requirements of this Act."

Section 112(a)(8) of the Act defines an "electric utility steam-generating unit" as "any fossil-fuel-fired combustion unit of more than 25 megawatts electric (MWe) that serves a generator that produces electricity for sale." A unit that cogenerates steam and electricity and supplies more than one-third of its potential electric output capacity and more than 25 MWe output to any utility power distribution system for sale is also considered an electric utility steam-generating unit (i.e., utility unit).

Section 112(n)(1)(A) also requires that:

- The EPA develop and describe alternative control strategies for hazardous air pollutants (HAPs) that may warrant regulation under section 112; and
- The EPA proceed with rulemaking activities under section 112 to control HAP emissions from utilities if EPA finds such regulation is appropriate and necessary after considering the results of the study.

ES.2 REGULATORY DETERMINATION

This report does not contain a determination as to whether or not regulations to control HAP emissions from utility units are appropriate and necessary. The Agency has deferred the regulatory determination until a later date.

ES.3 OVERVIEW APPROACH TO COMPLETING THE STUDY

The study included numerous separate and interrelated analyses. First, HAP emissions test data were gathered from 52 utility units (i.e., boilers), including a range of coal-, oil-, and natural gas-fired utility units. Second, the emissions test data along with facility specific information (e.g., boiler type, control device, fuel usage) were used to estimate HAP emissions from all 684 utility plants in the United States (U.S.). Third, a screening level hazard/risk assessment was completed to prioritize the HAPs for further analyses. Fourth, various priority HAPs were analyzed for inhalation and

multipathway exposures and risks and other potential impacts. In addition, potential control strategies were analyzed for the priority HAPs. The overall summary of the study is presented in Figure ES-1.

This report presents the findings of the study. The primary components of this report are: (1) a description of the industry; (2) an analysis of emissions data; (3) an assessment of hazards and risks due to inhalation exposures to 67 HAPs; (4) assessments of risks due to multipathway (inhalation plus non-inhalation) exposures to four HAPs (radionuclides, mercury, arsenic, and dioxins); and (5) a discussion of alternative control strategies.

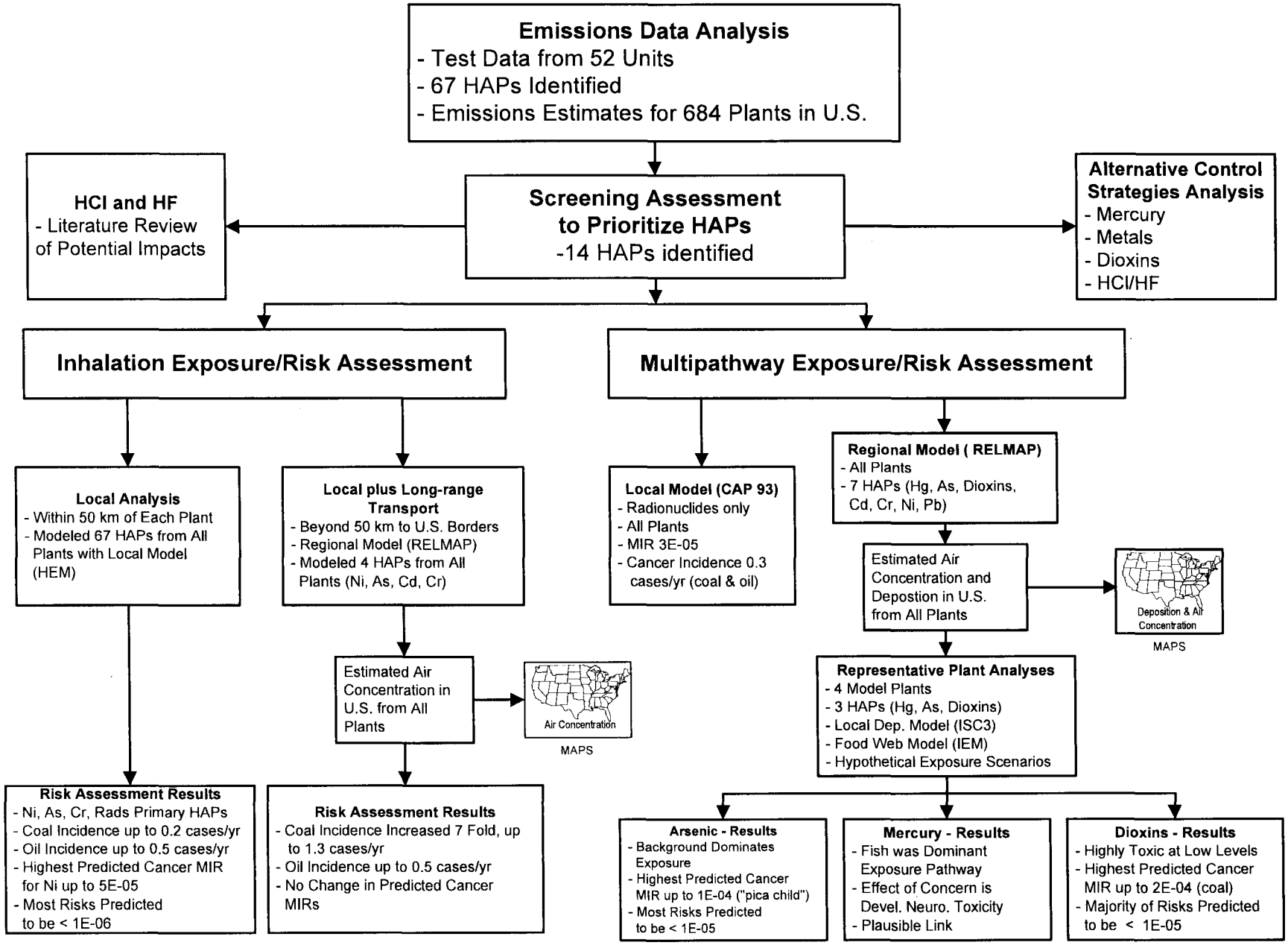
The study was based primarily on two scenarios: (1) 1990 base year emissions; and (2) 2010 emissions. In addition, emissions for 1994 were estimated using the most recent data. The 1990 scenario was chosen since that was the year the Amendments to the Act were passed and was the latest year for which utility operational data were available at the time the study was initiated. The 2010 scenario was selected to meet the section 112(n)(1)(A) mandate to evaluate hazards "after imposition of the requirements of the Act." Primarily, this meant assessing the hazards after the acid rain program is in place. The 2010 scenario also included estimated changes in HAP emissions resulting from projected trends in fuel choices and projected increases in electric power demands. However, the effects of other on-going or potential activities that were not factored into the 2010 projections (e.g., industry restructuring, new ozone and particulate matter [PM] standards, global climate change programs) may result in the 2010 projections being either underestimated or overestimated.

ES.4 EMISSIONS DATA ANALYSIS

A total of 684 utility plants (i.e., utilities) were identified as meeting the criteria for the study in 1990 in the U.S. These utilities are fueled primarily by coal (59 percent of total units), oil (12 percent), or natural gas (29 percent). Many plants have two or more units and several plants burn more than one type of fuel (e.g., contain both coal- and oil-fired units). In 1990, there were 426 plants that burned coal as one of their fuels, 137 plants that burned oil, and 267 plants that burned natural gas.

Emission estimates for the years 1990, 1994, and 2010 were based on emissions test data from 52 units obtained from extensive emission tests by the Electric Power Research Institute (EPRI), the Department of Energy (DOE), the Northern States Power Company, and the EPA. The testing program was designed to test a wide range of facility types with a variety of control scenarios; therefore, the data are considered generally representative of the industry. However, there are uncertainties in the data because of the small sample sizes for specific boiler types and control scenarios.

Figure ES-1. Overall Structure of Utility Air Toxics Study Analyses



These test data provided the basis for estimating average annual emissions for each of the 684 plants. A total of 67 of the 188 HAPs listed in section 112 of the Act were identified in the emissions testing program as potentially being emitted by utilities. Tables ES-1 and ES-2 present estimated emissions for, respectively, a subset of priority HAPs for 1990, 1994, and 2010, and for a set of characteristic boilers for 1994.

Although the EPA used average annual emissions estimates in assessing long-term exposures to individual HAPs on a national basis, emissions test data were not available for each utility in the U.S. Therefore, estimates for individual plants are particularly uncertain. Based on an uncertainty analysis, the average annual emissions estimates are expected to be roughly within a factor of plus or minus three of actual annual emissions. However, even this uncertainty analysis had limitations. For example, the uncertainty analysis did not include data on potential upsets or unusual operating conditions; therefore, the range of uncertainty could be greater.

ES.5 GENERAL APPROACH TO EXPOSURE AND RISK ASSESSMENT

Most of the risk assessment focused on inhalation exposure. All 67 HAPs were assessed for inhalation exposures, at least at a screening level. For many of the 67 HAPs, inhalation exposure is believed to be the dominant exposure pathway. However, for HAPs that are persistent and/or bioaccumulate, and are toxic by ingestion (or are radioactive), the non-inhalation exposure pathways could be more important. Based on a screening and prioritization assessment, which is described below, the EPA identified four high priority HAPs (radionuclides, mercury, arsenic, dioxins) to assess for non-inhalation exposures. In addition, cadmium and lead were identified as next highest priority. Multipathway assessments are presented for radionuclides, mercury, arsenic, and dioxins. The other two HAPs (lead and cadmium) were examined qualitatively for their potential for multipathway hazards.

ES.6 SCREENING ASSESSMENT

As outlined in Figure ES-1, EPA initially conducted a screening assessment that considered inhalation and non-inhalation exposure routes for all 67 HAPs to identify priority HAPs for more detailed assessment. To screen for inhalation exposures, the EPA used the Human Exposure Model (HEM) to model the 67 HAPs from all 684 utility plants utilizing generally conservative assumptions (i.e., assumptions that are more likely to overestimate rather than underestimate risks) to estimate inhalation risks for maximally exposed individuals (MEIs).

Table ES-1. Nationwide Utility Emissions for Thirteen Priority HAPs[a]

HAP	Nationwide HAP emission estimates (tons per year)[b]								
	Coal			Oil			Natural gas		
	1990	1994	2010	1990	1994	2010	1990	1994	2010
Arsenic	61	56	71	5	4	3	0.15	0.18	0.25
Beryllium	7.1	7.9	8.2	0.46	0.4	0.23	NM[c]	NM	NM
Cadmium	3.3	3.2	3.8	1.7	1.1	0.9	-	-	-
Chromium	73	62	87	4.7	3.9	2.4	-	-	-
Lead	75	62	87	11	8.9	5.4	0.43	0.47	0.68
Manganese	164	168	219	9.3	7.3	4.7	-	-	-
Mercury	46	51	60	0.25	0.2	0.13	0.0015	0.0017	0.024
Nickel	58	52	69	390	320	200	2.2	2.4	3.5
Hydrogen chloride	143,000	134,000	155,000	2,900	2,100	1,500	NM	NM	NM
Hydrogen fluoride	20,000	23,000	26,000	140	280	73	NM	NM	NM
Acrolein	25	27	34	NM	NM	NM	NM	NM	NM
Dioxins[d]	0.000097	0.00012	0.00020	1×10^{-5}	9×10^{-6}	3×10^{-6}	NM	NM	NM
Formaldehyde	35	29	45	19	9.3	9.5	36	39	57

[a] Radionuclides are the one priority HAP not included on this table because radionuclide emissions are measured in different units (i.e., curies per year) and, therefore, would not provide a relevant comparison to the other HAPs shown. Radionuclide emissions are presented in chapter 9.

[b] The emissions estimates in this table are derived from model projections based on a limited sample of specific boiler types and control scenarios. Therefore, there are uncertainties in these numbers (see section ES.4 for discussion).

[c] NM = Not measured.

[d] These emissions estimates were calculated using the toxic equivalency (TEQ) approach, which is based on the summation of the emissions of each congener after adjusting for toxicity relative to 2,3,7,8-tetrachlorodibenzo-p-dioxin (i.e., 2,3,7,8-TCDD).

Table ES-2. Estimated Emissions for Nine Priority HAPs from Characteristic Utility Units (1994; tons per year)[a]

Fuel:	Coal	Oil	Natural gas
Unit size (MWe):	**325**	**160**	**240**
Arsenic	0.0050	0.0062	0.0003
Cadmium	0.0023	0.0014	NC[b]
Chromium	0.11	0.0062	NC
Lead	0.021	0.014	NC
Mercury	0.05	0.0012	NC
Hydrogen chloride	190	9.4	NC
Hydrogen fluoride	14	NC	NC
Dioxins[c]	0.00000013	0.000000023	NC
Nickel	NC	1.7	0.004

[a] There are uncertainties in these numbers. Based on an uncertainty analysis, the EPA predicts that the emissions estimates are generally within a factor of roughly three of actual emissions.
[b] NC = Not calculated.
[c] See footnote d of Table ES-1.

If the MEI risk was above a minimum measure (e.g., exposure greater than one-tenth the inhalation reference concentration [RfC][a] or cancer risk greater than 1 chance in 10 million), then the HAP was chosen for more study. For non-inhalation exposures, the 67 HAPs were prioritized by considering five criteria: (1) persistence; (2) tendency to bioaccumulate; (3) toxicity; (4) emissions quantity; and (5) radioactivity.

Based on this screening assessment, a total of 14 HAPs were identified as priority. Twelve HAPs (arsenic, beryllium, cadmium, chromium, manganese, nickel, hydrogen chloride [HCl], hydrogen fluoride [HF], acrolein, dioxins, formaldehyde, and radionuclides) were identified as priority pollutants for further study based on potential for inhalation exposures and risks. Four of these 12 HAPs (arsenic, cadmium, dioxins, and radionuclides) plus 2 additional HAPs (mercury and lead) were considered priority for multipathway exposure); of these 6 HAPs, 4 (arsenic, mercury, dioxins, and radionuclides) were identified as the highest priority to assess for

[a] The RfC is an estimate (with uncertainty spanning perhaps an order of magnitude) of the daily inhalation exposure of the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious effects during a lifetime.

multipathway exposures and risks. Overall, a total of 14 of the 67 HAPs were considered priority. The other 53 HAPs were not evaluated beyond the screening assessment.

ES.7 INHALATION RISK ASSESSMENT -- LOCAL ANALYSIS

The EPA estimated inhalation exposures and risks due to dispersion of HAP emissions within 50 kilometers (km) of each of the 684 plants (i.e., local analysis). For 13 of the 14 priority HAPs, the HEM was used; for radionuclides, the Clean Air Act Assessment Package-1993 (CAP-93) model was used. The HEM exposure modeling conducted for the inhalation risk assessment was very similar to the modeling conducted for the screening assessment. The same default options and same input data were used. However, there is one important difference. For the inhalation risk assessment, a distinction was made between urban and rural locations. If a plant is located in an urban area, it was modeled using the urban mode (i.e., dispersion is assumed to be characteristic of emissions emitted by a facility in an urban location where there are buildings nearby). Dispersion of the pollutant plume in an urban area is expected to exhibit greater turbulence because of heat transfer and obstacles (i.e., large buildings). If a plant is located in a rural location, it was modeled using the rural mode (i.e., dispersion is assumed to be characteristic of a facility located in a rural location). In the screening assessment, all plants were modeled using the urban default because using the urban default typically leads to more conservative (i.e., higher) estimates of human exposures, which is appropriate for a screening assessment. However, using the urban and rural distinction is believed to reflect more realistic conditions.

The cancer risks for all gas-fired plants were well below one chance in one million (i.e., $< 1 \times 10^{-6}$) and no noncancer hazards were identified. Therefore, gas-fired plants are omitted from the following discussions.

In cases where data were missing or incomplete, the EPA had to make various assumptions. A few of these assumptions are more likely to overestimate risks. Other assumptions used are likely to underestimate risks. Based on an uncertainty analysis conducted for this study, it is estimated that these assumptions taken together lead to a reasonable high-end estimate (i.e., conservative, but within the bounds of reasonable estimates) of the risks due to inhalation exposure within 50 km of plants. Within the limits of current scientific information, this approach is, therefore, most likely to overestimate health risks for these pollutants. The uncertainty analysis suggests that the most likely estimated inhalation MIRs (i.e., central tendency MIRs) may be roughly 2 to 10 times lower than the high-end MIRs presented below. The average individual risks due to inhalation exposure to utility HAP emissions for the total exposed U.S. population (roughly 200,000,000 people) are predicted to be roughly 100 to 1000 times lower than the high-end inhalation MIRs.

ES.7.1 Inhalation Cancer Risks for Coal-Fired Utilities Based on Local Analysis (1990)

The vast majority of coal-fired plants (424 of the 426 plants) are estimated to pose lifetime cancer risks (i.e., increased probability of an exposed person getting cancer during a lifetime) of less than 1×10^{-6} due to inhalation exposure to utility HAP emissions. Only two of the 426 plants are estimated to potentially pose inhalation risks greater than 1×10^{-6} (see Figure ES-2).

The increased lifetime cancer MIR due to inhalation exposure to coal-fired utility HAP emissions, based on the local analysis, is estimated to be no greater than 3×10^{-6}. Arsenic and chromium are the HAPs contributing most to the inhalation risks (see Table ES-3). All other HAPs, including radionuclides, were estimated to present inhalation risks less than 1×10^{-6} for coal-fired units.

The cancer incidence in the U.S. due to inhalation exposure to HAPs (including radionuclides) from all 426 coal-fired plants **based on the local analysis** is estimated to be no greater than approximately 0.2 cancer case per year (cases/yr), or 1 case every 5 years. However, as described in later sections, the consideration of long-range dispersion of HAPs (beyond 50 km) results in increased estimates for cancer incidence.

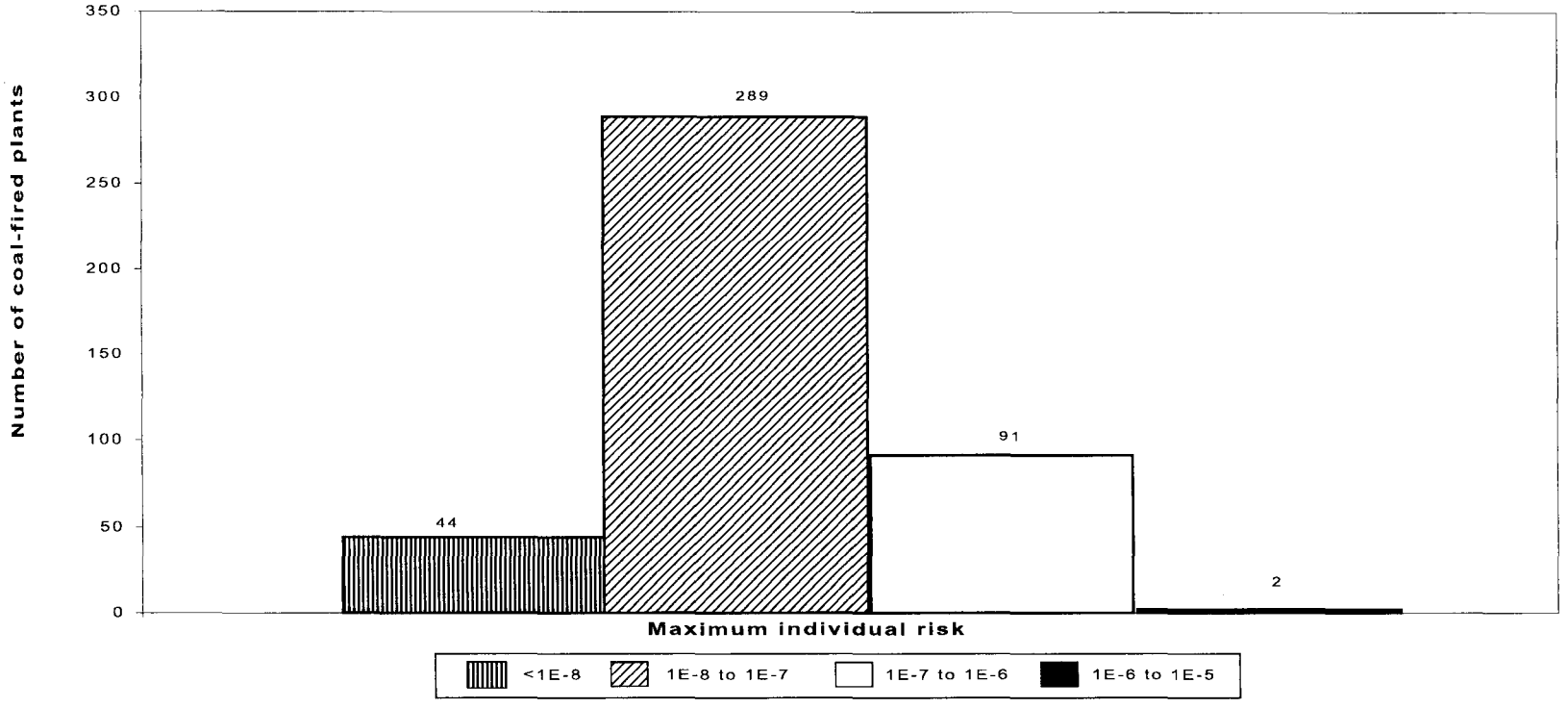
ES.7.2 Inhalation Cancer Risks for Oil-Fired Utilities Based on Local Analysis (1990)

The majority of the oil-fired plants (125 of the 137 plants) are estimated to pose inhalation cancer MIRs less than 1×10^{-6}. However, up to 11 of the 137 oil-fired plants are estimated to potentially present inhalation MIRs above 1×10^{-6} (see Figure ES-3). Nickel, arsenic, radionuclides, and chromium are the primary contributors to these cancer risks.

For oil-fired utilities, the highest contribution to the MIRs is from nickel. However, there are substantial uncertainties with the nickel risk estimates. Nickel is emitted in several different forms (e.g., nickel oxides, soluble nickel, sulfidic nickel) and the health effects of these different forms vary, and for some forms are unknown or uncertain. Nickel subsulfide (which is one of the possible forms of sulfidic nickel) is a known human carcinogen and appears to be the most carcinogenic form based on available data. Based on limited data, 3 to 26 percent of the nickel emissions are believed to be sulfidic nickel. It is not known how much of the sulfidic nickel emissions are nickel subsulfide. Several other nickel species (e.g., nickel oxides) are also potentially carcinogenic but the potencies are not known.

Figure ES-2. Number of Coal-Fired Utilities Posing Various Levels of Maximum Individual Risks (By Levels of MIR)

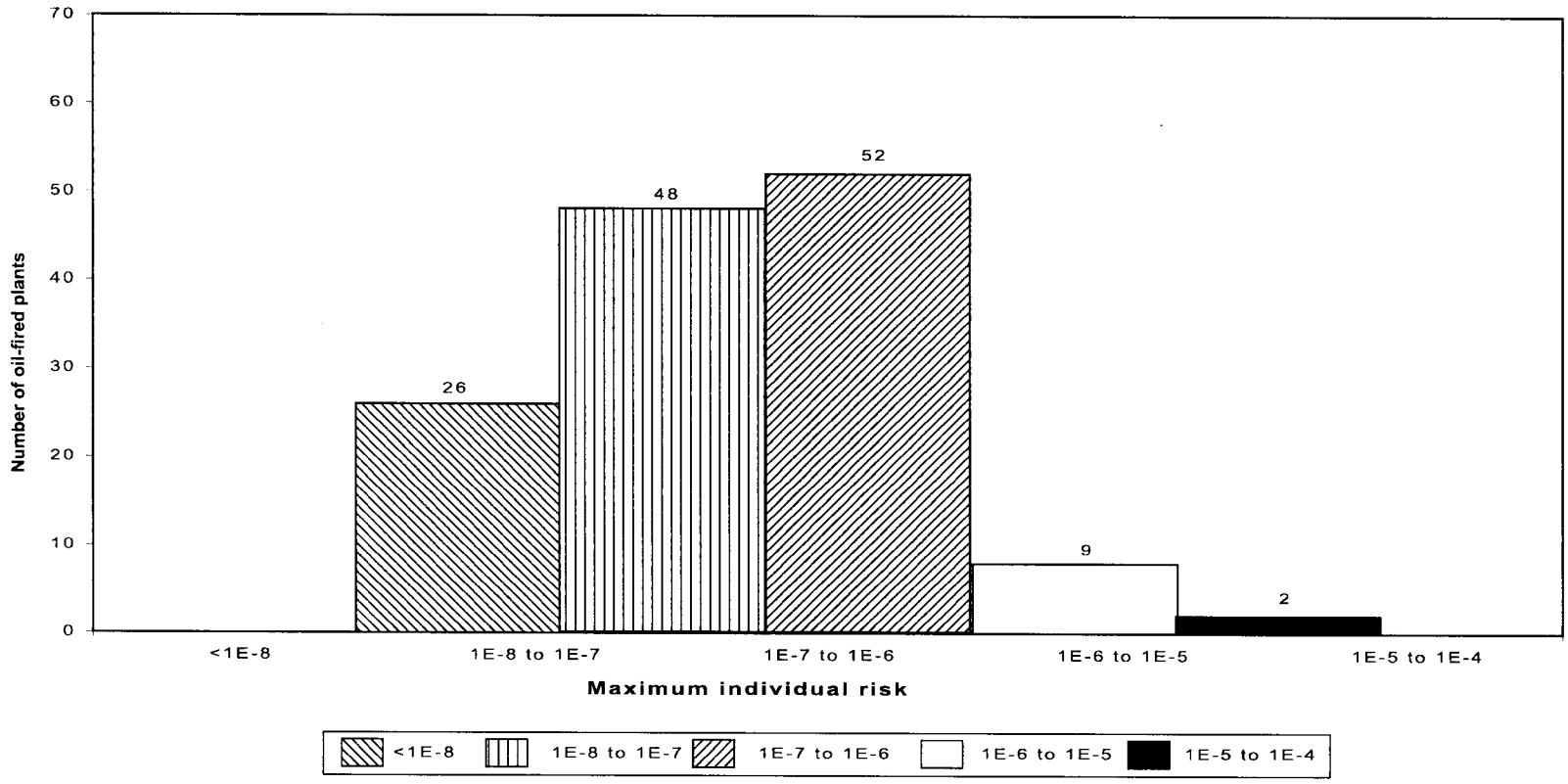
All carcinogenic non-radionuclide HAPs



Note: The high-end maximum individual risks (MIRs) are presented as exponents in this figure. For example, an increased cancer risk of one chance in one million (i.e., 1×10^{-6}) is shown as 1E-6 in this Figure. The figure shows that 91 plants are estimated to pose an MIR between 1×10^{7} and 1×10^{6} .

Figure ES-3. Number of Oil-Fired Utilities Posing Various Levels of Maximum Individual Risks (By Levels of MIR)

All carcinogenic non-radionuclide HAPs



Note: The MIRs are presented as exponents in this figure. For example, an increased cancer risk of 1×10^{-6} is shown as 1E-6 here. The figure shows there are 9 oil-fired plants with estimated MIRs between 1×10^{-6} and 1×10^{-5}.

Table ES-3. Summary of High-End Inhalation Cancer Risk Estimates from Local Analysis for Coal-Fired Utilities for the Year 1990

HAP	Highest Cancer MIR[a]	Population with lifetime risk > 1 x 10^{-6}	Number plants with MIR > 1 x 10^{-6}
Arsenic	2 x 10^{-6}	850	2
Chromium	1 x 10^{-6}	110	1
Total[b] (Aggregate of HAPs)	3 x 10^{-6}	850	2

[a] Estimated lifetime maximum individual risk (MIR) due to inhalation exposure for the "highest risk" coal-fired plant. Based on an uncertainty analysis, these estimates are considered reasonable high-end estimates (see section ES.7.4 for discussion).

[b] Estimated risk due to inhalation of the aggregate of HAPs assuming additivity of risk for 26 individual carcinogenic HAPs.

To evaluate the range of potential risks due to nickel emissions, the EPA estimated risks using various assumptions for nickel cancer potency (presented in chapter 6). For example, assuming the nickel mix is 50 percent as carcinogenic as nickel subsulfide, the highest inhalation cancer MIR due to the aggregate of HAP emissions from the highest risk oil-fired utility plant is estimated to be 6 x 10^{-5}. Assuming the nickel mix is 10 percent as carcinogenic as nickel subsulfide, the highest inhalation cancer MIR due to the aggregate of HAP emissions from the highest risk oil-fired utility plant is approximately 3 x 10^{-5}. The values in Table ES-4 and Figure ES-3 are based on the conservative assumption that the nickel mix is 50 percent as carcinogenic as nickel subsulfide.

Estimated risks due to inhalation exposure for a subset of HAPs based on the local analysis are presented in Table ES-4. All other HAPs analyzed were estimated to pose inhalation cancer risks below 1 x 10^{-6} for all 137 oil-fired plants.

The cancer incidence in the U.S. due to inhalation exposure to HAP emissions (including radionuclides) from all 137 oil-fired utilities, based on the local analysis, is estimated to be no greater than 0.5 cancer case/yr.

ES.7.3 Inhalation Cancer Risks Based on Long-Range Transport

In addition to the above analyses, the EPA conducted long-range transport analyses to assess emissions dispersion and exposures on a national scale for 1990. The Regional Lagrangian Model of Air Pollution (RELMAP) was used to estimate the dispersion of HAP emissions from the facility stack out to the borders of the continental U.S. This is in contrast to the HEM, which estimates dispersion and air concentrations within 50 km of the source.

Table ES-4. Summary of High-end Inhalation Cancer Risk Estimates Based on Local Analysis for Oil-Fired Utilities for the Year 1990

HAP	Highest MIR[a]	Population with lifetime risk > 1 x 10^{-6}	Number plants with MIR > 1 x 10^{-6}
Nickel[b]	5 x 10^{-5}	110,000	11
Arsenic	1 x 10^{-5}	2,400	2
Radionuclides	1 x 10^{-5}	2,400	2
Chromium	5 x 10^{-6}	2,300	1
Cadmium	2 x 10^{-6}	45	1
Total[c] (aggregate)	6 x 10^{-5}	110,000	11

[a] Estimated lifetime maximum individual risk (MIR) due to inhalation exposure for the "highest risk" oil-fired plant. Based on an uncertainty analysis, these estimates are considered reasonable high-end estimates (see section ES.7.4 for discussion).

[b] The estimates for nickel and total HAPs are based on the assumption that the mix of nickel compounds is 50 percent as carcinogenic as nickel subsulfide.

[c] Estimated risk due to inhalation of the aggregate of HAPs assuming additivity of risk for 14 individual carcinogenic HAPs.

The RELMAP modeling was conducted for all coal- and oil-fired utilities, but was limited to mercury, cadmium, chromium, arsenic, nickel, lead, and dioxins. Only inhalation exposures to the carcinogenic HAPs are discussed in this section. Deposition and multipathway concerns are discussed elsewhere in this report. The long-range transport modeling indicates that the local HEM analysis alone does not account for a substantial percentage of the population exposures due to coal-fired utility emissions. A comparison of the HEM results to the RELMAP results indicates a significant portion of emissions disperse further than 50 km, as would be expected for these HAPs, which are mostly fine particulate substances emitted from elevated stacks.

The RELMAP results for arsenic, cadmium, chromium, and nickel (which are emitted mainly as PM) were used to estimate the potential long-range transport inhalation exposures for other carcinogenic HAPs. Using this methodology, the highest cancer incidence due to inhalation exposure to HAPs from coal-fired utilities considering both local and long-range transport is estimated to be up to 1.3 cases/yr, which is about 7 times greater than the incidence estimated in the local analysis alone. The cancer incidence for oil-fired utilities did not change (see Table ES-5).

Table ES-5. Summary of High-End Inhalation Risk Estimates Due to Local and Long-Range Transport

LOCAL IMPACTS (dispersion within 50 km of each utility plant) [d]				
	OIL-FIRED PLANTS		**COAL-FIRED PLANTS**	
Pollutant	Maximum individual risk (MIR)	Annual increased cancer Incidence	Maximum individual risk (MIR)	Annual increased cancer incidence
Radionuclides	1×10^{-5}	0.2	2×10^{-8}	0.1
Nickel[a]	5×10^{-5}	0.2	7×10^{-7}	0.005
Chromium	5×10^{-6}	0.02	1×10^{-6}	0.02
Arsenic	1×10^{-5}	0.04	2×10^{-6}	0.05
Cadmium	2×10^{-6}	0.005	2×10^{-7}	0.0006
All Others[b]	8×10^{-7}	0.005	8×10^{-7}	0.004
Total[c]	6×10^{-5}	0.5	3×10^{-6}	0.2
LOCAL PLUS LONG-RANGE IMPACTS (dispersion from utility emission points to borders of continental U.S.)				
	OIL-FIRED PLANTS		COAL-FIRED PLANTS	
Pollutant	Maximum individual risk (MIR)	Annual increased cancer incidence	Maximum individual risk (MIR)	Annual increased cancer incidence
Radionuclides	1×10^{-5}	0.2	Not estimated	0.7
Nickel[a]	5×10^{-5}	0.2	1×10^{-8}	0.038
Chromium	5×10^{-6}	0.02	2×10^{-6}	0.15
Arsenic	1×10^{-5}	0.05	3×10^{-6}	0.37
Cadmium	2×10^{-6}	0.006	3×10^{-7}	0.005
All Others[b]	8×10^{-7}	0.006	1×10^{-6}	0.028
Total[c]	6×10^{-5}	0.5	4×10^{-6}	1.3

[a] Assumes that the nickel mixture is 50 percent as carcinogenic as nickel subsulfide.
[b] Estimated risks due to exposure to all remaining HAPs analyzed (i.e., excluding nickel, arsenic, chromium, cadmium, and radionuclides).
[c] Aggregate risk (risk due to inhalation exposure to all carcinogenic HAPs, assuming additivity of risks).
[d] There are uncertainties associated with these risk estimates. See sections ES.7.4 for discussion.

A comparison between the HEM local dispersion results and the long-range transport modeling results indicates that long-range transport is much less important for the MIR than it is for cancer incidence. For example, the MIR from the local analyses for coal-fired utilities (i.e., inhalation risk of 3×10^{-6}) is predicted to

increase by roughly 10 to 20 percent to about 4 x 10^{-6} when ambient concentrations are added from long-range transport of arsenic from all other utilities in the continental U.S. For oil-fired utilities, the long-range transport of HAPs has no impact on the highest inhalation MIR because of the remote location of the two highest risk oil-fired plants.

ES.7.4 Uncertainties with the Inhalation Cancer Risk Assessment

There are several areas of uncertainty in the inhalation risk assessment including: (1) the impacts of long-range transport; (2) the emissions and health effects of different forms of chromium and nickel; (3) the use of a linear non-threshold high-to-low dose extrapolation model for estimating cancer risks at low exposure concentrations; (4) the impacts of episodic releases resulting from upsets or unusual operating conditions; (5) how residence times and activity patterns impact the exposures; (6) the impacts on sensitive subpopulations; (7) the impacts of background exposures; and (8) the risk of complex pollutant mixtures.

The uncertainty analysis indicates that the inhalation cancer MIRs and incidence estimates presented above are reasonable high-end estimates of the risks due to inhalation exposure within 50 km of each plant. That is, the estimates are considered generally conservative (i.e., predicted to be roughly the 90th to 95th percentile). The uncertainty analysis suggests that the most likely estimated inhalation MIRs (i.e., central tendency MIRs) may be roughly 2 to 10 times lower than the high-end MIRs presented above. The average individual risks due to inhalation exposure to utility HAP emissions for the total exposed U.S. population (roughly 200,000,000 people) are predicted to be roughly 100 to 1,000 times lower than the high-end inhalation MIRs.

ES.7.5 Summary of the Inhalation Cancer Risks

For the majority of utility plants (approximately 671 of the 684 plants), the estimated inhalation cancer risks due to HAP emissions are less than 1 x 10^{-6}. However, several plants (2 coal plants and up to 11 oil plants) are estimated to potentially pose inhalation cancer risks above 1 x 10^{-6}. One oil plant is estimated to pose a high-end inhalation cancer MIR of up to 6 x 10^{-5}. Based on the assessment, no greater than 1.8 cancer cases/yr are estimated to occur in the U.S. due to inhalation exposure to HAP emissions from all coal- and oil-fired utilities. Further research and evaluation may be needed to more comprehensively assess the inhalation cancer risks, especially to reduce the uncertainties associated with the nickel risk estimates.

ES.7.6 Inhalation Noncancer Risks

The EPA also assessed noncancer risks (i.e., health effects other than cancer) due to short- and long-term inhalation exposure. Manganese, HCl, HF, and acrolein were found to be the four HAPs of highest potential concern for noncancer effects.

Based on modeling HAPs for all 684 plants with the HEM, estimated long-term ambient HAP concentrations were generally 100 to 10,000 times below the RfC or similar benchmark. The highest estimated long-term ambient HAP concentration was 10 times below the RfC.

Using a short-term air dispersion model that considers all reasonable meteorological conditions, EPA modeled maximum one-hour concentrations for three HAPs (HCl, HF, and acrolein). The highest short-term exposure was 140 times below the acute reference level.

ES.8 MERCURY MULTIPATHWAY ASSESSMENT

ES.8.1 Background Discussion for Mercury

Mercury cycles in the environment as a result of natural and human (anthropogenic) activities. The amount of mercury mobilized and released into the biosphere has increased since the beginning of the industrial age. Most of the mercury in the atmosphere is elemental mercury vapor, which circulates in the atmosphere for up to a year, and hence can be widely dispersed and transported thousands of miles from likely sources of emission. After it deposits, mercury commonly is emitted back to the atmosphere either as a gas or associated with particles, to be re-deposited elsewhere. As it cycles between the atmosphere, land, and water, mercury undergoes a series of complex chemical and physical transformations, many of which are not completely understood.

Mercury is a persistent element and bioaccumulates in the food web. Mercury accumulates most efficiently in the aquatic food web. Predatory organisms at the top of the food web generally have higher mercury concentrations. Nearly all of the mercury that accumulates in fish tissue is methylmercury. Inorganic mercury, which is less efficiently absorbed and more readily eliminated from the body than methylmercury, does not tend to bioaccumulate.

Fish consumption dominates the pathway for human and wildlife exposure to methylmercury. The EPA's 1997 Mercury Study Report to Congress supports a plausible link between anthropogenic releases of mercury from industrial and combustion sources in the U.S. and methylmercury in fish. However, these fish methylmercury concentrations also result from existing background concentrations of mercury (which may consist of mercury from natural sources, as well as mercury which has been re-emitted from the oceans or soils) and deposition from the global reservoir (which includes mercury emitted by other countries). Given the current scientific understanding of the environmental fate and transport of this element, it is not possible to quantify how much of the methylmercury in fish consumed by the U.S. population is contributed by U.S. emissions relative to other sources of mercury (such as natural sources and re-emissions from the global pool). As a result, it cannot be assumed that a change in total mercury emissions will be linearly related to any resulting change in methylmercury in fish, nor over what time period these changes would occur. This is an area of ongoing study.

ES.8.2 Methylmercury Health Effects

Epidemics of mercury poisoning following high-dose exposures to methylmercury in Japan and Iraq demonstrated that neurotoxicity is the health effect of greatest concern when methylmercury exposure occurs to the developing fetus. Dietary methylmercury is almost completely absorbed into the blood and distributed to all tissues including the brain; it also readily passes through the placenta to the fetus and fetal brain. The reference dose (RfD) is an amount of methylmercury, which when ingested daily over a lifetime is anticipated to be without adverse health effects to humans, including sensitive subpopulations. At the RfD or below, exposures are expected to be safe. The risk following exposures above the RfD is uncertain, but risk increases as exposures to methylmercury increase.

Extrapolating from the high-dose exposures that occurred in the Iraq incident, the U.S. EPA derived a RfD for methylmercury of 0.1 microgram per kilogram body weight per day (µg/kg bw/day). While the U.S. EPA was advised by scientific reviewers to employ this RfD for this analysis, new data are emerging. Currently ongoing are two large epidemiology studies in the Seychelle Islands and in the Faroe Islands that were designed to evaluate childhood development and neurotoxicity in relation to fetal exposures to methylmercury in fish-consuming populations. Because of various limitations and uncertainties in all of the available data, the U.S. EPA and other Federal agencies intend to participate in an interagency review of the human data on methylmercury, including the most recent studies from the Seychelle Islands and the Faroe Islands. The purposes of this review are to refine the estimates of the level of exposure to mercury associated with subtle neurological endpoints and to further consensus between all of the Federal agencies. After this process, the U.S. EPA will determine if a change in the RfD for methylmercury is warranted. (Note: see the 1997 EPA *Mercury Study Report to Congress* for further discussion and assessment of mercury health effects and public health impacts).

ES.8.3 Mercury Multipathway Exposure Assessment

Mercury was considered highest priority for multipathway exposure analysis. To assess the transport and deposition of mercury emissions from utilities and to estimate concentrations in environmental media and biota, three modeling efforts were undertaken: (1) long-range modeling, (2) local scale modeling, and (3) modeling of environmental concentrations. The RELMAP was used to predict long-range dispersion and deposition across the U.S. For the local analysis, a model designed to predict deposition of HAPs within 50 km, the Industrial Source Complex Version 3 (ISC3) air dispersion model, was used. Next, the EPA's Indirect Exposure Model Version 2M (IEM-2M) was used to estimate mercury environmental concentrations and human exposures. Hypothetical exposure scenarios were evaluated for four model plants (a large coal-fired, a medium coal-fired, a small coal-fired, and a medium oil-fired utility boiler). The analysis included three types of plant locations: (1) rural (agricultural), (2) near lakes

(lacustrine), and (3) urban. Three human fish consumption scenarios were considered.

The modeling provided information on whether local and/or long-range transport of mercury is significant in a variety of scenarios. The models indicate that most of the mercury from utilities is transported further than 50 km from the source. The fate and transport models provided an assessment of potential inhalation and ingestion exposures.

ES.8.4 Summary of Mercury Assessment Results for Utilities

Recent estimates of annual total global mercury emissions from all sources (natural and anthropogenic) are about 5,000 to 5,500 tons per year (tpy). Of this total, about 1,000 tpy are estimated to be natural emissions and about 2,000 tpy are estimated to be contributions through the natural global cycle of re-emissions of mercury associated with past anthropogenic activity. Current anthropogenic emissions account for the remaining 2,000 tpy. Point sources such as fuel combustion; waste incineration; industrial processes (e.g., chlor-alkali plants); and metal ore roasting, refining, and processing are the largest point source categories on a world-wide basis.

For the year 1994, coal-fired utilities were estimated to emit approximately 51 tpy of mercury in the U.S., which is estimated to be 33 percent of the 158 tpy of airborne anthropogenic emissions of mercury in the U.S. If one assumes that current anthropogenic activity represents between 40 and 75 percent of the total airborne emissions (anthropogenic plus other emissions [e.g., natural emissions]), one can calculate that U.S. utilities emit roughly 13 to 26 percent of the total (natural plus anthropogenic) airborne emissions of mercury in the U.S.

Given the global estimates of 5,000 to 5,500 tpy (which are highly uncertain), U.S. anthropogenic mercury emissions are estimated to account for roughly 3 percent of the global total, and U.S. utilities are estimated to account for roughly 1 percent of total global emissions.

A computer simulation of long-range transport of mercury emissions from all U.S. sources conducted for the EPA's 1997 Mercury Study Report to Congress suggests that about one-third (~ 52 tons) of the 158 tpy of U.S. anthropogenic emissions are deposited, through wet and dry deposition, within the lower 48 States. The remaining two-thirds (~ 107 tons) is transported outside of U.S. borders where it diffuses into the global reservoir. In addition, the computer simulation suggests that another 35 tons of mercury from the global reservoir is deposited for a total deposition of roughly 87 tpy in the U.S. Although this type of modeling is uncertain, the simulation suggests that about three times as much mercury is being added to the global reservoir from U.S. sources as is being deposited from it. What is not uncertain is that additional emissions to air will

contribute to levels in the global reservoir and deposition to water bodies.

Long-range transport modeling conducted as part of this Utility Study predicts that approximately 30 percent (15 tpy) of the utility mercury emissions deposit in the continental U.S. The estimated annual deposition rates resulting from utility mercury emissions range from 0.5 to greater than 10 micrograms per square meter. Long-range transport modeling also predicts that the highest deposition occurs in the eastern half of the U.S., particularly areas such as southeastern Great Lakes and Ohio River Valley, central and western Pennsylvania, large urban areas in the eastern U.S. (e.g., Washington, D.C., New York City) and various locations in the vicinity of large coal-fired utilities. Based on the limited available receptor monitoring data, the RELMAP model seems to be accurate within a factor of plus or minus 2. That is, the RELMAP model seems to over- and underestimate mercury values within a factor of two and appears to be relatively unbiased in its predictions.

The modeling assessment in conjunction with available scientific knowledge, supports a plausible link between anthropogenic mercury emissions and mercury found in freshwater fish. As noted above, there are many sources of mercury emissions worldwide, both natural and anthropogenic. The coal-fired utilities are one category of the mercury sources.

Mercury is considered the highest priority for multipathway analyses because it is an environmentally persistent, toxic element. Mercury is deposited to soil and terrestrial vegetation but at levels that do not result in human exposures likely to be detrimental to health through terrestrial exposure pathways. However, in its methylated form mercury bioaccumulates in the food web (especially the aquatic food web). Modeling results suggest that most of the mercury emitted to the atmosphere is deposited more than 50 km away from the source, especially sources that have tall stacks. As stated above, the modeling assessment from the Mercury Study in conjunction with available scientific knowledge, supports a plausible link between anthropogenic mercury emissions and mercury found in freshwater fish. Additional emissions to air will contribute to levels in the global reservoir and deposition to water bodies. As a result, mercury emissions from utility units may add to the existing environmental burden.

At this time, the available information, on balance, indicates that utility mercury emissions are of sufficient potential concern for public health to merit further research and monitoring. The EPA recognizes that there are substantial uncertainties that make it difficult to quantify the magnitude of the risks due to utility mercury emissions, and that further research and/or evaluation would be needed to reduce these uncertainties. Remaining questions include the following: (1) what is the quantitative relationship between a change in U.S. mercury emissions and the resulting change in

methylmercury levels in fish; (2) what are the actual consumption patterns and estimated methylmercury exposures of the subpopulations of concern; (3) what are the actual mercury levels in a statistically valid and representative sample of the U.S. population and susceptible subpopulations; (4) what exposure levels are likely to result in adverse health effects; (5) what affects the formation of methylmercury in waterbodies and its bioaccumulation in fish; (6) how much mercury is emitted from natural sources and past anthropogenic sources; and (7) how much mercury is removed during coal cleaning and other ongoing practices for pollution control. New data that could reduce some of the uncertainties are likely to become available in the next several years, and EPA plans to review and consider these data, as appropriate, in future decisions.

Regarding potential methods for reducing mercury emissions, the EPA has not identified any demonstrated add-on control technologies currently in use in the U.S. that effectively remove mercury from utility emissions. (However, there may be add-on control technologies used in other source categories that effectively reduce mercury emissions.) Based on available data, total mercury removal by existing PM control devices on coal-fired utilities varies considerably, ranging from 0 to 82 percent removal (with a median efficiency of 15 percent removal) for cold-side electrostatic precipitators (ESPs), and from 0 to 73 percent removal (with a median efficiency of 8 percent removal) for fabric filters. Also, hot-side ESPs exhibited no mercury control. Existing flue gas desulfurization (FGD) units exhibit limited mercury control, ranging from 0 to 62 percent removal, with a median removal of 23 percent. The mercury control efficiency of FGD units is a function of several factors including temperature, plant configuration, and type of coal. Pilot-scale studies have shown that mercury removal can be enhanced through the use of activated carbon injection. However, the limited results to date utilizing carbon injection are inconsistent and more data and research are needed. Other various pollution prevention strategies, such as coal cleaning, have shown some effectiveness in reducing utility emissions of mercury. Conventional coal cleaning removes, on average, approximately 21 percent of the mercury contained in the coal. Also, fuel switching, such as switching from coal to natural gas, would result in decreased emissions of mercury.

ES.9 SCREENING LEVEL MULTIPATHWAY ASSESSMENT FOR ARSENIC

Arsenic is a naturally occurring element found normally, in various concentrations, in soil. In addition, arsenic can also be naturally present in other media (e.g., various food sources and water). Arsenic levels have been measured in a variety of foods. Even though shellfish and other marine foods contain the greatest concentrations of total arsenic, much of the arsenic present in fish and shellfish exists in the less toxic organic form. Other food products, such as meats, rice, and cereals, contain higher percentages, and often higher total amounts, of inorganic arsenic, which is the form of primary toxicological concern.

Arsenic is also naturally present in trace amounts in coal and oil. When coal or oil are burned, some of this naturally occuring arsenic is released to the atmosphere. The quantity of arsenic released from any utility plant is dependent on many factors including the concentration of arsenic in the fuel, control device efficiency, and other factors.

Utilities emit about 62 tpy of arsenic nationwide, about 3 to 4 percent of the total anthropogenic arsenic emissions in the U.S. Because of its chemical and physical characteristics, arsenic emitted to the atmosphere may be transported to other environmental media (soil or water), thus allowing non-inhalation exposures to occur.

ES.9.1 Exposure Modeling

It was not possible to model every utility plant for arsenic multipathway exposures. Therefore, a screening level model plant approach was used. Four model plants (i.e., a large coal-fired, a medium coal-fired, a small coal-fired, and a medium oil-fired utility boiler) were designed to characterize typical utility plants. In taking the model plant approach, it was realized that there would be a great deal of uncertainty surrounding the predicted fate and transport of arsenic as well as the exposures. However, the assessment was useful for estimating potential risks due to utility arsenic emissions. Three models were used to predict environmental arsenic concentrations and exposure: the RELMAP, the ISC3, and the Indirect Exposure Model Version 2 (IEM-2). These models were used to predict the fate and transport of arsenic emissions and to estimate human exposures to arsenic through multiple exposure routes, including food consumption, water ingestion, and inhalation. Three basic exposure scenarios were considered: a subsistence farmer (adult and child), a subsistence fisher (adult and child), and a pica child (i.e., a child that ingests significant quantities of soil). These scenarios were considered because they represent possible high-end scenarios for exposure to arsenic.

ES.9.2 Health Effects of Arsenic

Inhalation exposure to inorganic arsenic has been strongly associated with lung cancer in humans. Human exposure to inorganic arsenic, via ingestion, has been associated with an increased risk of several types of cancer, including skin, bladder, liver, and lung cancers. Oral exposure to inorganic arsenic has also been associated with noncancer effects, including effects to the central nervous system, cardiovascular system, liver, kidney, and blood.

ES.9.3 Approach for Estimating Screening Level Arsenic Risks

Increased cancer risks were estimated for each hypothetical scenario, for the four model plants, each of which was placed in two different hypothetical locations (i.e., an eastern humid site and a dry western site). For each of the exposure scenarios, except for the pica child, it is assumed that the hypothetical person is exposed for 30 years. For the pica child, it is assumed that exposure occurs for

7 years. Risks were estimated by multiplying the estimated intakes of arsenic by the EPA's cancer potency factor for arsenic.

ES.9.4 Screening Level Arsenic Risk Assessment Results

The results of the screening level multipathway arsenic exposure assessment provide an indication of the potential hazards and risks that may occur due to emissions from a utility plant. However, the results are not applicable to any particular plant. There are uncertainties and limitations to the analysis.

Exposures to inorganic arsenic due to background levels and due to emissions from the model utility boilers were predicted to be mainly through the ingestion of grains. Exposure to inorganic arsenic through the ingestion of fish was not predicted to be a major pathway of exposure because there is considerable evidence that little of the total arsenic in fish tissue is inorganic arsenic. Soil ingestion is the major route of exposure to inorganic arsenic for the pica child.

ES.9.4.1 Arsenic Cancer Risks. The cancer risks due to multipathway exposures to inorganic arsenic, as estimated in the model plant analysis using hypothetical scenarios, due to utility emissions alone (no background) were estimated to range from 4×10^{-7} to 1×10^{-4}. The highest estimated risk (1×10^{-4}) was for a pica child assumed to be living at the point of maximum deposition. The arsenic emissions from the large coal-fired model utility boiler at the eastern humid site were estimated to pose this highest risk for the pica child. When the risk from background exposure (2×10^{-4}) is added to the maximum risk from utility exposure, the risk for the pica child is estimated to be up to 3×10^{-4}. The "pica child" is considered a high-end, conservative scenario.

Background exposures were estimated to dominate the exposures and risks in all scenarios. When considering only the arsenic emissions from the model utility units (not including background), in all scenarios it was the large coal-fired unit that was estimated to pose the greatest multipathway risks and the medium coal-fired unit was estimated to pose the next highest risks. The small coal-fired unit and the oil-fired unit were estimated to present lower risks.

ES.9.4.2 Uncertainty Discussion. There are uncertainties associated with the cancer risk estimates from arsenic. The analysis was based on model plants and hypothetical constructs; therefore, the results are not applicable for any specific utility plant. Further analyses are needed to better characterize the risks posed by arsenic emissions from utilities. A few uncertainties are discussed here.

Exposure to arsenic through the ingestion of tap or well water was not included in this assessment. The exposure modeling assessment was based on a model plant analysis, hypothetical scenarios, and incorporated data with varying degrees of uncertainty. Also, there are uncertainties associated with the health effects data for arsenic.

For example, the animal ingestion studies have not clearly shown an association between arsenic ingestion exposure and cancer.

ES.10 DIOXIN SCREENING LEVEL MULTIPATHWAY ASSESSMENT

The highest MEI inhalation cancer risk due to dioxin emissions from any utility plant based on the HEM analysis (described in section ES.7) was estimated to be 1×10^{-7}. The EPA estimates that coal-fired utilities emit 0.2 pounds per year (lb/yr) of dioxin (toxic equivalents, TEQ) and that oil-fired utilities emit 0.01 lb/yr. These estimates combined are roughly 1 percent of the nationwide anthropogenic dioxin emissions. However, dioxin emissions data were only available for twelve utility plants and 42 percent of the measurements were below the minimum detection limit. Moreover, dioxins are not part of the naturally occuring fossil fuel. They are formed in highly complicated reactions which may occur with unknown frequency during combustion. Therefore, the emissions data for dioxins from utilities, which are the basis of exposure modeling, are considered more uncertain than the emissions data for many of the other HAPs.

For the screening level multipathway analysis, the transport, deposition, multipathway exposures, and human cancer risks were assessed for utility emissions of polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs), collectively referred to as dioxins. Atmospheric deposition of dioxin emissions can be important because dioxins tend to persist in the environment and bioaccumulate in the food web. Environmental persistence and bioaccumulation, coupled with carcinogenic effects at very low levels, make multipathway exposure an important consideration for dioxins.

ES.10.1 Methods

The basic approach for estimating screening level multipathway exposures to dioxins was similar to the methods described above for mercury and arsenic. However, there were some differences. The EPA's ISCST3 model was used to predict deposition and air concentrations of dioxins within 50 km of each of four model plants. Model plants were selected to represent both large and small coal- and oil-fired utilities. A modified version of the IEM spreadsheet model was used to estimate environmental concentrations, exposures to the environmental concentrations for 16 hypothetical human scenarios, and the resulting cancer risks. Pathways assessed include inhalation, dermal contact with soil, and ingestion of water, soil, fish, plants, and animals.

ES.10.2 Results

Since the analysis was based on model plants, using hypothetical scenarios, the results are not applicable to any specific plant and contain substantial uncertainties about the risks due to dioxin emissions. Total modeled screening level lifetime cancer risks related to multipathway exposure to dioxins for the four-model plant analysis ranged from 1×10^{-10} to 2×10^{-4}. The results of this

analysis indicate that the exposures and risks due to fish consumption are the highest of all pathways considered. The highest modeled result of 2×10^{-4} lifetime cancer risk was obtained for the subsistence fisher exposure scenario. In all modeled scenarios, the non-inhalation exposures were at least one order of magnitude larger than the inhalation exposures, thus demonstrating the potential significance of including multipathway exposure analysis in the risk assessments for pollutants that are environmentally persistent and tend to bioaccumulate. Also, unlike the results for arsenic, modeled exposures to dioxins for each pathway exceed the background exposure estimates for dioxins.

ES.10.3 Uncertainty Discussion

Several sensitivity analyses were completed for the screening level multipathway assessment of utility dioxin risks to assess the reasonableness of the results. The assumptions with the greatest impact on the predicted risk to the subsistence fisher were those made about the biota-sediment accumulation factor. This sensitivity analysis suggests that the modeling results are reasonable for a screening level analysis.

ES.11 MULTIPATHWAY ASSESSMENT FOR RADIONUCLIDES

Radionuclide emissions from utilities may result in human exposure from multiple pathways including: (1) external radiation exposure from radionuclides suspended in air or deposited on the ground, and (2) internal exposure from the inhalation of airborne contaminants or ingestion of contaminated food. The CAP-93 model was used to estimate multipathway exposures and risks due to radionuclide emissions to humans within 50 km of all 684 utilities. However, this assessment did not use site-specific data for the non-inhalation exposure analysis, but rather relied on various generic assumptions and general input data.

Based on the CAP-93 modeling, 667 of the 684 plants are estimated to pose multipathway risks less than 1×10^{-5}. The highest estimated multipathway radiation exposure for the MEI due to radionuclide emissions from utilities was predicted to be 1.5 millirems (mRems) per year, which is estimated to pose an increased cancer risk of 3×10^{-5}. Seventeen plants (13 coal- and 4 oil-fired plants) were estimated to pose multipathway risks between 1×10^{-5} and 3×10^{-5}. The estimated cancer incidence in the U.S., due to emissions and dispersion of radionuclides within 50 km of each utility, is estimated to be 0.3 cancer deaths/yr. The cancer incidence appears to be mostly due to inhalation exposure. The non-inhalation exposures contribute only slightly to the incidence. The non-inhalation exposure pathways have a greater impact on the MEIs, especially for coal-fired plants.

The risks due to exposure to radionuclides from utilities are substantially lower than the risks due to natural background radiation. The average exposure to natural background radiation (excluding radon) for the U.S. population has been estimated to be

roughly about 100 mRems per year, which is about 67 times higher than the highest exposure due to utility radionuclide emissions.

ES.12 QUALITATIVE MULTIPATHWAY EXPOSURE ASSESSMENT

The EPA recognizes that non-inhalation exposure pathways could be important for additional HAPs that are persistent and tend to bioaccumulate. A few additional HAPs that were not modeled for multipathway exposures are discussed below.

ES.12.1 Cadmium and Lead

Cadmium emissions from the vast majority of plants (683 of the 684 plants) are estimated to pose inhalation risks less than 10^{-6}, and the highest modeled air concentration of lead was 200 times below the national ambient air quality standard (NAAQS). Cadmium and lead are persistent, may bioaccumulate, and are toxic by ingestion. However, since the emission quantities and inhalation risks are relatively low, the EPA does not plan to conduct future evaluations of multipathway exposures of cadmium and lead from utilities.

ES.12.2 Nickel and Chromium

Nickel and chromium were not considered to be priority for non-inhalation exposures. At relatively high oral doses, nickel and chromium do cause noncancer toxicity. However, there are considerable uncertainties about the noncancer toxicity of nickel and chromium at relatively low ingestion doses (below the toxic threshold). Also, it is uncertain whether they pose a carcinogenic risk by ingestion. Hence, EPA does not plan to assess multipathway exposures for nickel and chromium for utilities.

ES.13 POTENTIAL IMPACTS OF HYDROGEN CHLORIDE AND FLUORIDE

No exceedances of the health benchmarks (e.g., RfCs) for HCl or HF were identified in the inhalation exposure assessment. However, emissions of HCL and HF may contribute to acid deposition and, to a lesser extent to PM fine and visibility problems. To the extent that these emissions may contribute to such problems, they could be addressed through other Titles of the Act.

ES.14 ALTERNATIVE CONTROL AND PREVENTION STRATEGIES

There are numerous potential alternative control strategies for reducing HAPs. These include precombustion controls (e.g., fuel switching, coal switching, coal cleaning, coal gasification), combustion controls, post combustion controls (e.g., PM controls, SO_2 controls), and approaches that prevent pollution by improving efficiency in supply (e.g., promoting energy efficiency in combustion) or demand (e.g., demand side management [DSM], pollution prevention, energy conservation). The degree of feasibility, cost, and effectiveness of each of these potential control technologies varies. For example, coal cleaning tends to remove at least some of all the trace metals, with lead concentrations being removed to the greatest

extent (averaging approximately 55 percent removal) and mercury being removed the least (averaging approximately 21 percent). Existing PM controls tend to effectively remove the trace metals (with the exception of mercury) while FGD units remove trace metals less effectively and exhibit more variability. Fuel switching (e.g., switching from coal to natural gas) could result in substantial reductions in HAP emissions. There are few existing data that show the HAP reduction effectiveness of DSM, pollution prevention, and energy conservation. These control strategies need to be examined further for technical and economic considerations.

ES.15 OTHER ISSUES AND FINDINGS

ES.15.1 Emissions and Risks for the Year 2010

In addition to the 1990 analysis, the EPA also estimated emissions and inhalation risks for the year 2010. There are substantial data gaps and uncertainties in the projections to the year 2010. However, the approach utilized is reasonable given the limitations of data to complete such projections.

Based on EPA's assessment for this report, HAP emissions from coal-fired utilities are predicted to increase by 10 to 30 percent by the year 2010. Predicted changes that were included in the 2010 emissions projections include the installation of scrubbers for a small number of facilities, the closing of a few facilities, and an increase in fuel consumption of other facilities. However, based on EPA's exposure modeling analysis for the year 2010, the inhalation risks in 2010 for coal-fired utilities are estimated to be roughly equivalent to the 1990 inhalation risks. For oil-fired plants, emissions and inhalation risks are estimated to decrease by 30 to 50 percent by the year 2010. Multipathway risks for 2010 were not assessed. Utilization of add-on controls to comply with the acid rain program are not expected to significantly impact on HAP emissions due to their limited numbers and limited HAP control efficiency improvement. However, if additional actions are taken to reduce emissions of criteria pollutants, acid rain precursors, or global warming compounds (e.g., use of fuel switching or add-on controls to reduce SO_x, NO_x, and/or carbon dioxide emissions), these actions could result in reductions in HAP emissions. For example, analyses performed to assess compliance with the revised NAAQS for ozone and PM indicate that mercury emissions in 2010 may be reduced by approximately 16 percent (11 tpy) over those projected in this report. Other potential (but unknown) actions (e.g., repowering, restructuring) may have a significant impact on HAP emissions; however, these unknowns were not included in the 2010 projection.

ES.15.2 Peer Review

Draft versions of Chapters 1 through 9 and 13 of this report and draft technical support documents were reviewed by many non-EPA scientists representing industry, environmental groups, academia, and other parties. Chapters 10, 11, and 12 are new chapters produced in response to major comments from the reviewers. EPA held a scientific

peer review meeting and also a public meeting in July 1995 to obtain comments from reviewers. In February, April, and September 1996, all sections of the draft report underwent additional review by EPA, State and local Agencies, and other Federal Agencies. Additional review occurred during 1997. The EPA has revised the report, as appropriate, based on the reviewers' comments. However, there were several comments that could not be fully addressed because of limitations in data, methods, and resources. In addition, there were some comments that EPA did not agree with. Also, the new chapters (10 to 12) have only undergone a limited review. Draft versions of this report, along with all the comments received, have been submitted to the public docket (A-92-55) at the following address: U.S. EPA, Air and Radiation Docket and Information Center, mail code 6102, 401 M Street, S.W., Washington, D.C. 20460; telephone number (202) 260-7548. Materials are available for public review at the docket center or copies may be mailed (for a fee) on request by calling the above number.

ES.15.3 Industry Report

If alternative methods and assumptions were used to study the HAP emissions from utilities, the results would likely be somewhat different. To assess the impact of using alternative assumptions and methods, it is useful to compare the EPA study with a similar study completed by the EPRI.

The EPRI prepared a report, entitled "Electric Utility Trace Substances Synthesis Report," (November 1994) that paralleled the EPA's study. Many of the same emissions data were used and similar risk assessment methods were utilized. The EPRI study concluded that cancer inhalation risks are below 1×10^{-6} for all utilities, and noncancer inhalation risks are well below Federal threshold levels for all utilities. Population inhalation risks were determined by the EPRI to be insignificant (less than 0.1 cancer case/year). Case studies at four plants found that multimedia risks, including mercury, are below levels of concern.

The EPRI's risk estimates are generally similar to, but in several cases lower than, those of EPA. Differences between the studies include: (1) EPA's use of a higher unit risk factor for arsenic; (2) EPA's assumption that nickel was carcinogenic (EPRI assumed nickel was not carcinogenic); (3) EPA's evaluation of exposure beyond 50 km to all locations in the U.S. (EPRI did not attempt this analysis); (4) EPRI's radionuclide analysis was based on several model plants, while the EPA evaluated every plant in the U.S.; and (5) the EPRI assumed that chromium emissions were five percent chromium VI (the carcinogenic form), while EPA assumed that 11 percent (for coal-fired plants) and 18 percent (for oil-fired plants) were chromium VI. In addition, the EPRI mercury multimedia study considered only the local impact from four plants (not worst-case) and did not include potential impacts of total nationwide utility mercury emissions and contributions to total environmental loadings.

ES.15.4 Potential Environmental Impacts Not Included in Study

There are other potential environmental issues associated with utilities not assessed in this report. These include: (1) the impacts of criteria pollutants (SO_2, NO_x, PM, carbon monoxide, and ozone) or acid rain precursors (SO_2 and NO_x), which are studied and regulated under other sections of the Act; (2)an assessment of ecological impacts of HAPs; (3) the impacts of carbon dioxide emissions and climate; and (4) the impacts resulting from restructuring, mining, drilling, solid waste disposal, transmission, transportation, or other activities associated with electric power generation. These issues and potential impacts were not assessed because they were considered beyond the scope of this study as mandated by Section 112(n) of the Act.

ES.15.5 Link to Particulate Matter

Arsenic, cadmium, chromium, lead, nickel, radionuclides, and several other HAPs are emitted primarily as PM. Consequently, these HAPs may contribute to PM emissions and PM health concerns, especially from poorly controlled coal-fired units and uncontrolled oil-fired units (about two-thirds of oil-fired units are uncontrolled for PM). Impacts for PM were not addressed in this study, but are being studied under Title I of the Act. If additional controls of PM emissions are utilized, this could result in reductions in HAP emissions.

ES.16 OVERALL TECHNICAL SUMMARY AND CONCLUSIONS

Based on available information and current analyses, the EPA believes that mercury from coal-fired utilities is the HAP of greatest potential concern and merits additional research and monitoring. There are uncertainties regarding the extent of risks due to mercury exposures including those from utility emissions. Further research and evaluation are needed to gain a better understanding of the risks and impacts of utility mercury emissions. In addition, further research and evaluation of potential control technologies and strategies for mercury are needed.

For a few other HAPs, there also are still some remaining potential concerns and uncertainties that may need further study. First, the screening multipathway assessments for dioxins and arsenic suggest that these two HAPs are of potential concern (primarily from coal-fired plants); however, further evaluations and review are needed to better characterize the impacts of dioxins and arsenic emissions from utilities. Second, nickel emissions from oil-fired utilities are of potential concern, but significant uncertainties still exist with regards to the nickel forms emitted from utilities and the health effects of those various forms. The impacts due to HAP emissions from gas-fired utilities are negligible based on the results of this study; therefore, the EPA feels that there is no need for further evaluation of the risks of HAP emissions from natural gas-fired utilities.

ES.17 AREAS FOR FURTHER RESEARCH AND ANALYSIS

There are many uncertainties and data gaps described throughout this report. This section summarizes several important areas in which further research or scientific work may be needed.

ES.17.1 Emissions Data for Dioxins

Emissions data for dioxin compounds were available from less than 12 utility plants. Many of the measurements were near the detection limits. Therefore, there are greater uncertainties with the dioxin emissions than for the other HAPs. Research may be needed to gain a better understanding of the dioxin emissions from utilities and the dioxin formation, if any, in various utility boiler types (e.g., units with cold-side or hot-side ESPs).

ES.17.2 Speciation of Nickel

There are significant uncertainties regarding the forms of nickel emitted from oil-fired utilities and their associated health effects. Research would be useful to determine the emissions quantities of various nickel forms and the health effects of various nickel forms.

ES.1.7.3 Multipathway Risk Assessment

Further work may be needed to better characterize the risks due to multipathway exposure to certain HAPs (e.g., arsenic and dioxins).

ES.17.4 Local, Regional, and Long-range Transport Exposures

Further modeling and evaluation may be needed to better characterize the impacts of local, regional, and long-range transport of HAPs from utilities.

ES.17.5 Mercury

There are numerous areas regarding mercury that may need further research, study, or evaluation. A few potential areas for further study include the following:

(1) additional data on mercury content of various types of coal;

(2) improved methods for measuring mercury levels in water;

(3) the impact of reducing mercury emissions from coal-fired facilities on the bioaccumulation of mercury in fish;

(4) statistically valid and reliable estimates of methylmercury exposure levels in the U.S. population and susceptible subpopulations, as measured in human hair;

(5) the occupational, dietary and behavioral factors that affect mercury exposures for people who are determined to be exposed above a threshold of concern;

(6) the human health and environmental benefits that would be expected by reducing mercury emissions from U.S. utilities;

(7) control technologies or pollution prevention options that are available, or will be available, that could potentially reduce mercury emissions and what are the costs of those options;

(8) how do other regulations, programs and activities (e.g., acid rain program, electricity restructuring, NAAQSs, and climate change) affect mercury emissions; and

(9) additional data on mercury emissions (e.g., how much is emitted from various types of units, how much is divalent vs elemental mercury, and how do factors such as control device, fuel type, and plant configuration affect emissions and speciation).

Several additional uncertainties and potential areas for further research on mercury are discussed in other sections of this report.

ES.17.6 Projections to the Year 2010

There are significant uncertainties and unknowns in the emissions and risk projections made to the year 2010 (e.g., impact of electricity restructuring; impact of State efforts to regulate such restructuring; impact of any climate change abatement initiatives). Research and evaluation in these areas may be needed.

ES.17.7 Ecological Risks

The effects of HAPs on wildlife, endangered species, and terrestrial and aquatic ecosystems were not evaluated in this study. Although not mandated by section 112(n)(1)(A), further evaluation of ecological risks due to HAP emissions would be needed to fully evaluate the impacts of utility HAP emissions.

ES.17.8 Criteria Pollutant and Acid Rain Programs

Further evaluation is needed to assess the impacts of the Acid Rain and Criteria Pollutant programs (e.g., impact of revisions to the PM-fine and ozone NAAQS; impact of Ozone Transport Assessment Group [OTAG] activities) on HAP emissions, especially for mercury.

1.0 INTRODUCTION

This chapter presents an introduction to the study of hazardous air pollutant (HAP) emissions from electric utility steam-generating units (i.e., utilities). The chapter is divided into three main sections: the legislative mandate that requires this report, the provisions of the 1990 amendments to the Clean Air Act (CAA or the Act) related to this study, and an overview of the utility study and its approach to meeting the provisions of the Act.

1.1 LEGISLATIVE MANDATE

In section 112(n)(1)(A) of the Act, Congress directs the U.S. Environmental Protection Agency (EPA) to:

> "... perform a study of the hazards to public health reasonably anticipated to occur as a result of emissions by electric utility steam generating units of ... [HAPs] ... after imposition of the requirements of this Act."

Section 112(a)(8) of the Act defines an "electric utility steam-generating unit" as "any fossil-fuel-fired combustion unit of more than 25 megawatts electric (MWe) that serves a generator that produces electricity for sale." A unit that cogenerates steam and electricity and supplies more than one-third of its potential electric output capacity and more than 25 MWe output to any utility power distribution system for sale is also considered an electric utility steam-generating unit.

Section 112(n)(1)(A) also requires that:

- Results of this study be presented in a report to Congress by November 1993;
- The EPA develop and describe alternative control strategies for HAPs that may warrant regulation under section 112; and
- The EPA proceed with rulemaking activities under section 112 to control HAP emissions from utilities if it determines from the study that such regulation is appropriate and necessary.

Section 112(n)(1)(A) does not include a requirement to analyze the cost(s) of alternative control strategies in the study. Therefore, no cost analyses (e.g., control costs, economic, cost-benefit) have been performed as a part of this study. These analyses would be conducted as part of the rulemaking process should EPA determine that regulations are appropriate and necessary.

The EPA began work in 1991 to develop and collect the information and data needed to prepare this study of HAP emissions from electric utilities. At that time, only a small amount of reliable data on HAP

emissions from utilities were available. In October 1996, the Agency published a three-volume report, *Study of Hazardous Air Pollutant Emissions from Electric Utility Steam Generating Units--Interim Final Report*. (EPA-453/R-96-013). This final report incorporates additional analyses and includes more recent data on emissions, control technologies, and health effects.

This report discusses the possible impact of pollution controls required by other Federal regulations or sections of the Act, estimates which HAPs are present in utility unit emissions, and estimates exposures and risk to humans from the emission of these HAPs.

1.2 CAA PROVISIONS AND STUDIES RELATED TO THIS STUDY

The CAA contains several provisions relating to electric utilities that will impact the industry well into the future. Environmental regulations implementing many of these requirements are now in effect; others have been established since the date of the last report; and others are under development.

This section summarizes the major provisions of the Act affecting electric utilities and their relevance to this study. These include nonattainment provisions, acid deposition control programs, and new source performance standards (NSPS) discussed in sections 1.2.1 through 1.2.3. The development of regulations for HAP under section 112 of the Act and other related studies required by section 112 are discussed in sections 1.2.4 and 1.2.5, respectively.

1.2.1 Nonattainment Provisions

Title I of the Act includes requirements for attaining and maintaining the national ambient air quality standards (NAAQS). Section 108 of the Act directs EPA to identify certain pollutants which may reasonably be anticipated to endanger public health and welfare. Section 109 directs the Administrator to establish primary and secondary NAAQS for the identified pollutants. Under section 110 of the Act and related provisions, States are primarily responsible for ensuring attainment and maintenance of the ambient standards. The EPA has established NAAQS for six criteria pollutants: ozone (O_3), carbon monoxide (CO), particulate matter (PM), lead, sulfur dioxide (SO_2), and nitrogen oxides (NO_x) under Title 40, Part 50 of the Code of Federal Regulations (40 CFR Part 50). Electric utilities are significant emitters of SO_2 and NO_x; NO_x emissions from electric utilities account for about one-third of nationwide emissions.[1] Electric utilities also emit other criteria pollutants such as PM as well as air toxics.

The EPA issued revised NAAQS for O_3 and PM on July 18, 1997 (*Federal Register*, volume 62, page 38856 [62 FR 38856]). The new rules strengthened the primary standard for O_3, added standards for PM less than 2.5 microns in size ($PM_{2.5}$) to supplement the PM_{10} primary standard, and revised secondary standards.[2] As part of this

rulemaking, the EPA also proposed rules requiring States to develop programs to reduce regional haze.

To achieve the new standards, EPA has developed an integrated strategy that will require reductions in NO_x and SO_2 as well as volatile organic compounds (VOC) and PM. Nitrogen oxide is a precursor to the formation of ground-level O_3, and SO_2 is a precursor to the formation of PM in the atmosphere. Electric utilities will be affected as States reduce emissions to meet the new standards. One EPA study predicts that nationwide NO_x reductions ranging from 25 to 90 percent, depending on the particular State or non-attainment area, will be needed to attain the revised O_3 ambient standard.[3]

The Regulatory Impact Analysis for the revised standards assumes that much of the needed emission reductions would be achieved through the Acid Deposition Program for SO_2 and NO_x discussed in section 1.2.2 and through the revised NSPS discussed in section 1.2.3. According to the analysis, SO_2 and NO_x emissions from utilities will be reduced by approximately 40 and 50 percent, respectively, by the year 2010.[4] These analyses also estimate a 16 percent reduction (approximately 11 tons per year) in utility mercury emissions (in 2010) as a result of compliance with the revised NAAQS (primarily related to the impact of the SO_2 strategy to meet the PM NAAQS).[5]

In a related action, EPA proposed rules requiring 22 States and the District of Columbia to submit State Implementation Plans (SIPs) that address the regional transport of ground-level O_3. The proposed rule would decrease ozone transport in the eastern half of the United States by reducing NO_x emissions. Under the proposed rule, States may reduce emissions from sources they choose, although utility and large nonutility point sources are expected to be affected. Implementation of the proposed rule would reduce total emissions of NO_x by 35 percent based on analyses by EPA and the Ozone Transport Assessment Group (OTAG). The EPA estimates that this action will bring areas into attainment with the revised O_3 standard without additional local controls. Many of these States are expected to reduce NO_x emissions by participating in the cap-and-trade program discussed in section 1.2.2.[6]

1.2.2 Acid Deposition Control

Title IV of the Act sets as its primary goal the reduction of annual SO_2 emissions by 10 million tons below 1980 levels. To achieve these reductions, the law requires a two-phase tightening of the restrictions placed on fossil-fuel power plants (i.e., utilities). Phase I of EPA's SO_2 Program (40 CFR Parts 72 through 75) began in 1995 and affects 263 units at 110 mostly coal-burning electric utility plants in 21 States. An additional 182 units joined Phase I as substitution or compensating units, bringing the total of Phase I units to 445. Emissions data indicate that 1995 SO_2 emissions at these units nationwide were reduced by almost 40 percent below their required level of 8.7 million tons.[7] The second phase begins in the year 2000 and covers an additional 1,600 boilers. The EPA believes the 10 million ton goal will be met before the year 2010. To reduce

SO_2 emissions, an affected source may: (1) install flue gas scrubbers, (2) switch to a fuel that contains less sulfur, or (3) purchase emission allowances. The control option a utility selects to comply with the SO_2 reduction requirements may also have an effect on HAP emissions.

Under the SO_2 program, affected units are allocated allowances based on their historic fuel consumption and a specific emissions rate. Each allowance permits a unit to emit one ton of SO_2 per year. For each ton discharged, one allowance is retired. Allowances may be bought, sold, or banked and are tracked through a computerized system. However, no source can emit at a level violating Federal or State limits set under Title I of the Act. Sources also must obtain a permit and meet continuous emission monitoring requirements for SO_2, NO_x, and carbon dioxide (CO_2), as well as volumetric flow and opacity monitoring requirements.

Section 407 of the Act establishes the NO_x Emission Reduction Program with the goal of reducing emissions by 2 million tons from 1980 levels. Like the SO_2 emission reduction program, the NO_x program is implemented in two phases beginning in 1996 and 2000. Under Phase I rules (40 CFR Part 76), approximately 277 dry-bottom wall-fired boilers and tangentially-fired boilers (Group I) must meet applicable annual average emission rates of 0.45 pound per million British thermal units (lb/MMBtu) and 0.50 lb/MMBtu, respectively, by January 1, 1996. Utilities can meet the limits by installing low-NO_x burner technology or other combustion control technology or by averaging emissions among several units. An affected unit also may obtain an alternative emission limit under specified conditions. Implementation of Phase I will decrease annual NO_x emissions by over 400,000 tons per year (tpy) between 1996 and 1999 (60 FR 18751, April 13, 1995).[8,9]

The EPA issued final rules implementing Phase II of the program in late 1996 (61 FR 67112, December 19, 1996). In these rules, EPA determined that more effective low NO_x burner technology is available to establish more stringent standards for Phase II, Group I boilers than those established for Phase I. Emission limits for Group II boilers (wet bottom, cyclones, cell burners, and vertically-fired boilers) were also established based on NO_x control technologies comparable in cost to low NO_x burners (selective catalytic reduction [SCR]). Selective catalytic reduction is a commercially available flue gas treatment technology that injects ammonia into the flue gas in the presence of a catalyst. The catalyst promotes reactions that convert NO_x to nitrogen and water. By the year 2000, the Phase II rule (affecting 775 units) will achieve an additional reduction of 1.17 million tons of NO_x per year. Phase I and Phase II together are estimated to decrease nationwide annual NO_x emissions by 2.06 million tpy beginning in the year 2000.[10]

The final Phase II rule includes an option allowing a State or group of States to petition EPA to accept an emissions cap-and-trade program as a substitute for compliance with the Group 2 limits and

additional reductions required for Group 1 boilers. The petition may be granted if the Administrator finds that alternative compliance through the cap-and-trade program will achieve lower total NO_x emissions from Group 1 and Group 2 boilers than if the new limits were applicable. The Phase I limits established in 1995 would apply to Group 1 boilers in a cap-and-trade program. This provision is expected to affect boilers located in the OTAG region which contains about 87 percent of the units covered by the Phase II rule.[10]

In related developments, the EPA is currently developing a model cap-and-trade program to facilitate NO_x emission reductions from large stationary sources choosing to participate. The Agency intends to propose the rule in early 1998 and finalize the action in conjunction with the ozone transport rulemaking in September 1998.[11]

1.2.3 New Source Performance Standards

Section 111 of the Act requires the development of NSPS for newly constructed or modified affected facilities. Section 403 of the Act, as amended, revised the definition of the term "standard of performance" to mean:

> "...a standard for emissions of air pollutants which reflects the degree of emission reduction achievable through the application of the best system of emission reduction which (taking into the cost of achieving such reduction and any nonair quality health and environmental impact and energy requirements) the Administrator determines has been adequately demonstrated."

New source performance standards currently provide the major regulatory authority for the control of air emissions from utilities. Fossil-fuel-fired steam generating units greater than 73 MW heat input that were constructed or modified after August 17, 1971, are subject to requirements of 40 CFR Part 60, Subpart D; units constructed or modified after September 18, 1987, are subject to 40 CFR Part 60, Subpart Da. These rules define "fossil fuel" as "natural gas, petroleum, coal, and any form of solid, liquid, or gaseous fuel derived from such material for the purpose of creating useful heat." Fossil fuels include coal (bituminous, subbituminous, anthracite, lignite), oil (Nos. 2, 4, and 6), and natural gas. Subparts D and Da include limits for emissions of SO_2, NO_x, and PM based primarily on the use of scrubbers or low sulfur coal, combustion modification techniques (overfire air, low excess air, and reduced heat release rate), and PM control devices. Provisions also are included for the use of continuous opacity monitoring systems and continuous emission monitoring systems for SO_2 and NO_x and oxygen (O_2) or CO_2.

Section 407 of the Act requires EPA to revise the NSPS for NO_x emissions from utility and nonutility units to reflect improvements in emission reduction methods. The EPA proposed revisions to the NO_x limit for utility units (i.e., boilers) in 40 CFR Part 60, Subpart Da (regardless of fuel type) based on coal-firing and the performance of SCR control technology, in combination with combustion controls (62 FR

36947; July 9, 1997). Thus, units can meet the proposed standards by using clean fuels such as natural gas or by installing more effective control systems. The proposed rule also revised the emission limit to incorporate an output-based format that will encourage unit operating efficiency and pollution prevention. The EPA estimates that about 43,600 tons of NO_x per year would be emitted from 17 new utility boilers expected to be constructed over the next 5 years. The proposed revised standards would reduce these emissions by about 25,800 tpy.[12]

The NSPS program results indirectly in the control of some HAPs. For example, NSPS that limit emissions of PM will also control HAPs that are PM or that condense onto the PM in the affected gas streams. Furthermore, the use of SO_2 scrubbers (currently on about 14 percent of the units) will also control some vapor-phase HAPs, such as hydrogen chloride (HCl) and hydrogen fluoride (HF), in addition to providing some control of mercury.

1.2.4 Hazardous Air Pollutants

Section 112(d) of the Act requires that EPA promulgate regulations for the control of HAPs listed in section 112(b) of the Act from both new and existing major sources. A "major" source means a source that:

> "... emits or has the potential to emit, considering controls, 10 tons per year or more of any HAP or 25 tons per year or more of any combination of HAPs."

Regulations developed under section 112(d) must reflect the maximum degree of reduction in emissions of HAP that is achievable, taking into consideration the cost of achieving the emissions reduction, and any non-air quality health and environmental reduction and energy requirements. This level of control is commonly known as the maximum achievable control technology (MACT). For new sources, MACT standards cannot be less stringent than the emission control that is achieved in practice by the best-controlled similar source. The MACT standards for existing sources cannot be less stringent than the average emission limitation achieved by the best-performing 12 percent of existing sources for categories and subcategories with 30 or more sources, or the best-performing 5 sources for categories or subcategories with fewer than 30 sources. Section 112(d) also provides that the Administrator may distinguish among classes, types, and sizes of sources within a source category when establishing standards. Regulations for the control of HAP emissions from utilities will be developed under this authority if such regulations are determined to be necessary and appropriate.

1.2.5 Other Studies

The 1990 amendments to section 112 of the Act also mandate five other related studies: (1) the mercury study, (2) the National Institute of Environmental Health Sciences (NIEHS) health effects of mercury study, (3) the National Academy of Sciences (NAS) risk

assessment methodologies study, (4) the Great Waters study, and (5) the Presidential Risk Commission.

1.2.5.1 Mercury Study. Section 112(n)(1)(B) requires the EPA to complete a study of mercury emissions from utilities, municipal waste combustion units, and other sources, including area sources, by November 15, 1994. The study is to consider the rate and mass of mercury emissions, the health and environmental effects of such emissions, technologies that are available to control such emissions, and the costs of such technologies. The EPA just recently (December 19, 1997) published the *Final Mercury Study Report to Congress*. The 3-year delay was necessary to allow sufficient time for data gathering, analyses, writing, and extensive peer review. The Mercury Study is closely related to this Utility Study because utilities are the largest anthropogenic source of mercury emissions. Utilities (primarily coal-fired utilities) are estimated to emit approximately 33 percent of the airborne anthropogenic mercury in the United States. Several analyses and conclusions contained in the Mercury Study are applicable to utilities, and are discussed in Chapter 7 of this report.

1.2.5.2 NIEHS Health Effects of Mercury Study. Under section 112(n)(1)(c), the NIEHS is required to perform a study identifying the threshold level of mercury exposure that would not adversely affect human health. A report on the NIEHS study was published in 1993.[13]

1.2.5.3 NAS Risk Assessment Methodologies Study. In January 1995, the NAS finalized a report[14] on the risk assessment methodologies used by the EPA. The results of the NAS study were consulted to help develop the methodologies for the risk assessment portions of this study.

1.2.5.4 The Great Waters Study. In response to section 112(m), the EPA finalized a report in May 1994 on the atmospheric deposition of pollutants to the "Great Waters," namely, the Great Lakes, Chesapeake Bay, Lake Champlain, and coastal waters.[15] The pollutants of concern to the Great Waters study that are emitted from utilities include lead, cadmium, dioxins, and, in particular, mercury. The report discussed the following:

- The contribution of atmospheric deposition to pollutant loadings in these waters
- Environmental and public health effects of atmospheric pollution that is deposited to these waters
- Sources of pollutants deposited to these waters.

The May 1994 report noted that the Great Waters are polluted by HAPs that originate from local and distant sources; however, more data are needed to identify sources of the pollutants. The recommendations of the May 1994 Great Waters report were: (1) the EPA should strive

to reduce emissions of the pollutants of concern through implementation of the Act; (2) a comprehensive approach should be taken, both within the EPA and with other agencies, to reduce and preferably prevent pollution in air, water, and soil; and (3) the EPA should continue to support research for emissions inventories, risk assessment, and regulatory benefits assessment.

Following the first Report to Congress, the EPA published the "Final Water Quality Guidance for the Great Lakes System" required by section 118(c)(2) of the Clean Water Act (60 FR 15366, March 23, 1995). This guidance document established minimum water quality criteria, methodologies, policies, and procedures for the Great Lakes System. States and Tribes in the Great Lakes Basin were required to incorporate these provisions into their water quality standards and National Permit Discharge Elimination System permit programs by March 1997. In the guidance, EPA recognized that non-point sources of mercury, particularly by air deposition, are the most significant remaining contributors of mercury to the Great Lakes System. The EPA followed the guidance with the "Final Water Quality Guidance for the Great Lakes System Draft Mercury Permitting Strategy," released for public comment in June 1997 (62 FR 31025). The final permitting strategy will be finalized in the near future.

The second report to Congress on the atmospheric deposition of pollutants to the Great Waters was completed in June 1997. The report confirmed, and provided additional support for, the findings of the first Report to Congress that persistent and bioaccumulative toxic pollutants and excessive nitrogen can adversely affect the environmental condition of the Great Waters. Electric utilities and mobile sources are identified, in modeling studies and emission data, as major contributors of NO_x to the Chesapeake Bay and its watershed.[16]

1.2.5.5 Presidential Risk Commission. In section 303 of Title III of the 1990 amendments to the Act, Congress directed that the President form a Commission whose mandate would be to "...make a full investigation of the policy implications and appropriate uses of risk assessment and risk management in regulatory programs under various Federal laws to prevent cancer and other chronic human health effects which may result from exposure to hazardous substances." This Commission has issued the report in two volumes. Volume 1 entitled, "Framework for Environmental Health Risk Assessment," was issued in February 1997. Volume 2 entitled, "Risk Assessment and Risk Management in Regulatory Decision-Making," was issued in April 1997.

1.3 OVERVIEW AND APPROACH OF ELECTRIC UTILITY HAP STUDY

This report is the result of the work of government and nongovernment personnel. Emissions testing and emission estimation issues were discussed among numerous branches within the EPA and among representatives of industry, the Electric Power Research Institute (EPRI), and the Department of Energy (DOE). In particular, EPRI, DOE, and the EPA coordinated their utility emissions testing to cover more

plant configurations and obtain as much information as possible for the assessment. Portions of this report, and the data and methodologies utilized, were reviewed by numerous scientific experts within and outside the Agency. Outside reviewers included representatives from industry, other Federal agencies, State and local agencies, academia, and environmental organizations.[a]

The report is organized as follows. The electric utility industry is described in Chapter 2, including the types of fossil fuels, boilers, and air pollution control devices in use in the year 1990, as well as changes in control devices and fuel usage expected for the year 2010. Chapter 3 describes emissions testing conducted since 1990, the determination of emission modification factors (EMFs) from test reports, and the estimation of emissions for several characteristic units using a computer emission factor program. Chapter 4 introduces the health hazard assessment. The screening risk assessment used to determine the priority HAPs is described in Chapter 5. Chapter 6 discusses the inhalation route for HAP exposure, while Chapters 7 through 11 address multipathway exposures to mercury, lead, cadmium, radionuclides, arsenic, and dioxins. Chapter 12 discusses the potential impacts of HCl and HF. Alternative control strategies for HAP emissions reductions are given in Chapter 13. Chapter 14 presents the conclusions of the study. Additional supporting material is provided in the appendices.

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[a] Reviewers provided comment through a variety of venues (e.g., EPA Work Group, scientific peer review, Federal interagency review, public comment period). However, participation by a reviewer did not imply agreement with the methodology or conclusions presented by the EPA. All comments were considered during revision of the document.

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7.0 MERCURY ASSESSMENT

7.1 OVERVIEW

Mercury is a highly persistent, naturally occurring metal in the environment. Mercury is typically found in the environment in the elemental state Hg(0). When it bonds to other chemical elements, it is commonly found as a cation. The mercuric ion may bind to a number of inorganic anions; these are generally referred to as species of divalent mercury (Hg[II]). The mercuric ion may also form one or two bonds with a methyl group forming either monomethyl- or dimethylmercury.

The tendency of this metal to bioaccumulate in aquatic food webs has been well documented.[1-3] Mercury is toxic to humans from both the inhalation[4] and oral exposure routes.[4-6] Mercury is also toxic to other mammals[7-10]and to birds.[11-18] Questions remain regarding both the quantity of mercury and the duration of the exposure required to elicit responses in humans and animals, but it is widely accepted that exposures to mercury produce neurotoxicity. Mercury contamination of freshwater fish is a potential concern in the United States as indicated by numerous fish advisories[19] and mercury-related water quality standards issued by State Agencies. The 1997 EPA *Mercury Study Report to Congress*[20] presents a more complete assessment of the health effects, exposures, risks, ecological effects, sources, and control technologies. This chapter presents an abbreviated assessment of mercury as it is relevant to utilities, which is largely based on information presented in EPA's *Mercury Study Report to Congress*.[20]

Fish consumption dominates the pathway for human and wildlife exposure to methylmercury. The EPA's 1997 *Mercury Study Report to Congress* supports a plausible link between anthropogenic releases of mercury from industrial and combustion sources in the United States and methylmercury in fish. However, these fish methylmercury concentrations also result from existing background concentrations of mercury (which may consist of mercury from natural sources, as well as mercury which has been re-emitted from the oceans or soils) and deposition from the global reservoir (which includes mercury emitted by other countries). Given the current scientific understanding of the environmental fate and transport of this element, it is not possible to quantify how much of the methylmercury in fish consumed by the U.S. population is contributed by U.S. emissions relative to other sources of mercury (such as natural sources and re-emissions from the global pool). As a result, it cannot be assumed that a change in total mercury emissions will be linearly related to any resulting change in methylmercury in fish, nor over what time period these changes would occur. This is an area of ongoing study.

7.1.1 The Mercury Cycle

Environmental mercury passes through various environmental compartments and may change physical form and chemical species during

24. California Air Resources Board. Initial Statement of Reasons for Rulemaking. Proposed Identification of Nickel as a Toxic Air Contaminant. 1991.

25. American Conference of Governmental Hygienists. *Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*. 1995.

26. Memorandum from Maxwell, William, EPA to the EPA Air Docket No. A-92-55. March 8, 1996. Dioxin from Hot-side ESP units.

27. Letter and enclosure from Peck, Stephen C., Electric Power Research Institute, to Maxwell, William H., EPA:ESD. September 15, 1995. Transmittal of unlicensed electric utility trace substances synthesis report.

28. National Research Council. *Science and Judgment in Risk Assessment*. National Academy of Sciences, Washington, DC. 1994.

29. Office of Science and Technology Policy, Executive Office of the President. Chemical Carcinogens: A Review of the Science and Its Associated Principles. Washington, DC. 50 *Federal Register* 10372. March 14, 1985.

30. U.S. Environmental Protection Agency. Guidelines for Developmental Toxicity Risk Assessment: Office of Health and Environmental Assessment, 54 *Federal Register* 6398-63826, 1991.

31. U.S. Environmental Protection Agency. *A Descriptive Guide to Risk Assessment Methodologies for Toxic Air Pollutants*. EPA-453/R-93-038. Office of Air Quality Planning and Standards, Research Triangle Park, NC. 1993.

this process; these movements are conceptualized as a cycle. The mercury cycle has been studied and described in several recent reports and its understanding continues to undergo refinement.[3,21-24]

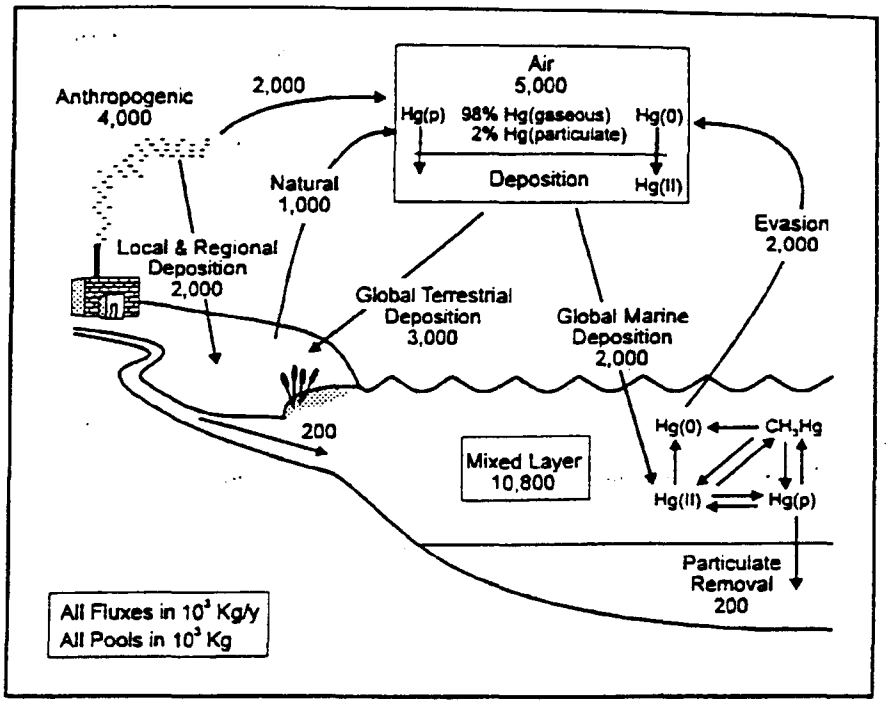
Given the present understanding of the mercury cycle, the flux of mercury from the atmosphere to land or water at any one location is comprised of contributions from: the natural global cycle; the global cycle perturbed by human activities; regional sources; and local sources. Recent advances allow for a general understanding of the global mercury cycle and the impact of anthropogenic sources. It is more difficult to make accurate generalizations of the fluxes on a regional or local scale due to the site-specific nature of emission and deposition processes.

7.1.1.1 The Global Mercury Cycle Past and Present. As a naturally occurring element, mercury is present throughout the environment in both environmental media and biota.[25] In a 1979 report edited by Nriagu, various authors estimated the global distribution of mercury and concluded that by far the largest repository is ocean sediments. Ocean sediments contain an estimated 10^{17} g of mercury, mainly as HgS. According to estimates in the report edited by Nriagu, ocean waters contain around 10^{13} g, soils and freshwater sediments 10^{13} g, the biosphere 10^{11} g (mostly in land biota), the atmosphere 10^{8} g, and freshwater contains on the order of 10^{7} g. This budget excludes "unavailable" mercury in mines and other subterranean repositories. A more recent estimate of the global atmospheric repository by Fitzgerald[3] is 25 Mmol or approximately 5×10^{9} g; this is 50 times the previous estimate of Nriagu.[25]

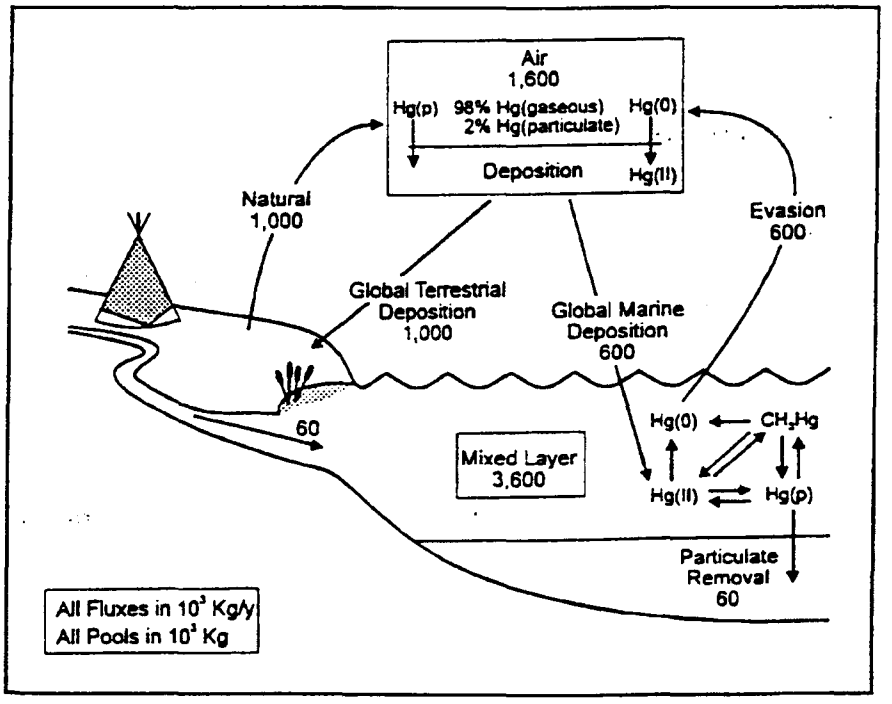
Recent estimates of annual total global mercury emissions from all sources (natural and anthropogenic) are about 5,000 to 5,500 tpy.[26] Of this total, about 1,000 tpy are estimated to be natural emissions and about 2,000 tpy are estimated to be contributions through the natural global cycle of re-emissions of mercury associated with past anthropogenic activity. Current anthropogenic emissions account for the remaining 2,000 tpy. Point sources such as fuel combustion; waste incineration; industrial processes (e.g., chlor-alkali plants); and metal ore roasting, refining, and processing are the largest point source categories on a world-wide basis. Given the global estimates of 5,000 to 5,500 tpy (which are highly uncertain), U. S. anthropogenic mercury emissions are estimated to account for roughly 3 percent of the global total, and U. S. utilities are estimated to account for roughly 1 percent of total global emissions.

A number of different techniques have been used to estimate the pre-industrial mercury concentrations in environmental media before anthropogenic emissions contributed significantly to the global mercury cycle. Figure 7-1 shows estimated current and preindustrial budgets and fluxes. It is difficult to separate current mercury concentrations by origin (i.e., anthropogenic or natural) because of the continuous cycling of the element in the environment. For

Estimated Current Mercury Budgets and Fluxes



Estimated Pre-Industrial Mercury Budgets and Fluxes



Source: Adapted from Mason et al., 1994.

Figure 7-1. Comparison of Estimated Current and Pre-Industrial Mercury Budgets and Fluxes

example, anthropogenic releases of elemental mercury may be oxidized and deposit as divalent mercury far from the source; the deposited mercury may be reduced and re-emitted as elemental mercury only to be deposited again continents away. Not surprisingly, there is a broad range of estimates and a great deal of uncertainty with each. When the estimates are combined, they indicate that between 40 and 75 percent of the current atmospheric mercury concentrations are the result of anthropogenic releases. The Expert Panel on Mercury Atmospheric Processes[27] concluded that pre-industrial atmospheric concentrations constitute approximately one-third of the current atmospheric concentrations. The panel estimated that anthropogenic emissions may currently account for 50-75 percent of the total annual input to the global atmosphere.[27] The estimates of the panel are corroborated by Lindqvist et al.,[28] who estimated that 60 percent of the current atmospheric concentrations are the result of anthropogenic emissions and Porcella,[29] who estimated that this fraction was 50 percent. Horvat et al.[30] assessed the anthropogenic fraction as constituting 40 to 50 percent of the current total. This overall range appears to be in agreement with the several-fold increase noted in inferred deposition rates.[31,32,33] The percentage of current total atmospheric mercury which is of anthropogenic origin may be much higher near mercury emissions sources.

A better understanding of the relative contribution of mercury from anthropogenic sources is limited by substantial remaining uncertainties regarding the level of natural emissions as well as the amount and original source of mercury that is re-emitted to the atmosphere from existing reservoirs. Recent estimates indicate that of the approximately 200,000 tons of mercury emitted to the atmosphere since 1890, about 95 percent resides in terrestrial soils, about 3 percent in the ocean surface waters, and 2 percent in the atmosphere.[27] More study is needed before it is possible to accurately differentiate natural fluxes from these reservoirs from re-emissions of mercury originally released from anthropogenic sources. For instance, approximately one-third of total current global mercury emissions are thought to cycle from the oceans to the atmosphere and back again to the oceans, but a major fraction of the emissions from oceans consists of recycled anthropogenic mercury. It is believed that as little as 20 to 30 percent of the current oceanic emissions are from mercury originally mobilized by natural sources.[34] Similarly, a potentially large fraction of terrestrial and vegetative emissions consists of recycled mercury from previously deposited anthropogenic and natural emissions.[27]

Comparisons of contemporary (within the last 15-20 years) measurements and historical records indicate that the total global atmospheric mercury burden has increased since the beginning of the industrialized period by a factor of between two and five. Contamination from some anthropogenic processes that are no longer in use produces continuing significant releases to surface water, groundwater, and the atmosphere. It is estimated that the mercury content of typical lakes and rivers has been increased by a factor of

two to four since the onset of the industrial age.[25] For example, analysis of sediments from Swedish lakes shows mercury concentrations in the upper layers that are two to five times higher than those associated with pre-industrialized times. More recently, researchers in Sweden estimated that mercury concentrations in soil, water and lake sediments have increased by a factor of four to seven in southern Sweden and two to three in northern Sweden in the 20th century.[23] In Minnesota and Wisconsin, an investigation of whole-lake mercury accumulation indicates that the annual deposition of atmospheric mercury has increased by a factor of three to four since pre-industrial times. Similar increases have been noted in other studies of lake and peat cores from this region; results from remote lakes in southeast Alaska also show an increase, though somewhat lower than found in the upper midwest United States.[27]

Although it is accepted that atmospheric mercury burdens have increased substantially since the preindustrial period, it is uncertain whether overall atmospheric mercury levels are currently increasing, decreasing, or remaining stable. Measurements over remote areas of the Atlantic Ocean show increasing levels up until 1990 and a decrease for the period 1990-1994.[35] At some locations in the upper Midwest of the United States, measurements of deposition rates suggest decreased deposition. However, other measurements at remote sites in northern Canada and Alaska show deposition rates that continue to increase.[36,37] Since these sites are subject to global long-range sources and few regional sources, these measurements may indicate a still increasing global atmospheric burden. More research is necessary; a multi-year, world-wide atmospheric mercury measurement program may help to better determine current global trends.[38]

7.1.1.2 Regional and Local Mercury Cycles. According to one estimate, roughly one half of the total anthropogenic mercury emissions eventually enter the global atmospheric cycle;[39] the remainder is removed through local or regional cycles. Mercury emissions from utilities are believed to exist primarily in two forms, divalent or elemental mercury. Divalent mercury, or Hg(II), is a positive ion (missing two electrons) with a electric charge of plus 2 (i.e., Hg^{++}, or oxidized mercury). Elemental mercury, or Hg(0), has a neutral charge (i.e., Hg^{0}). An estimated 5 to 10 percent of primary Hg(II) emissions are deposited within 100 km of the point of emission and a larger fraction on a regional scale. Hg(0) that is emitted may be removed on a local and regional scale to the extent that it is oxidized to Hg(II). Some Hg(0) may also be taken up directly by foliage; most Hg(0) that is not oxidized will undergo long-range transport due to the insolubility of Hg(0) in water. In general, primary Hg(II) emissions will be deposited on a local and regional scale to the degree that wet deposition processes remove the soluble Hg(II). Dry deposition may also account for some removal of atmospheric Hg(II). Assuming constant emission rates, the quantity of mercury deposited on a regional and local scale can vary depending on source characteristics (especially the species of mercury emitted), meteorological and topographical attributes, and other factors.[27] For

example, deposition rates at some locations have been correlated with wind trajectories and precipitation amounts.[40,41] Although these variations prohibit generalizations of local and regional cycles, such cycles may be established for specific locations. For example, unique mercury cycles have been defined for Siberia on a regional scale[42] and for the area downwind of a German chlor-alkali plant on a local scale.[43] Mercury cycles dependent on local and regional sources have also been established for the Upper Great Lakes region[44,45] and the Nordic countries.[40]

While the overall trend in the global mercury burden since pre-industrial times appears to be increasing, there is some evidence that mercury concentrations in the environment in certain locations have been stable or decreasing over the past few decades. For example, preliminary results for eastern red cedar growing near industrial sources (chlor-alkali, nuclear weapons production) show peak mercury concentrations in wood formed in the 1950s and 1960s, with stable or decreasing concentrations in the past decade.[27] Some results from peat cores and lake sediment cores also suggest that peak mercury deposition in some regions occurred prior to 1970 and may now be decreasing.[31,32,33,37] Data collected over 25 years from many locations in the United Kingdom on liver mercury concentrations in two raptor species and a fish-eating grey heron indicate that peak concentrations occurred prior to 1970. The sharp decline in liver mercury concentrations in the early 1970s suggests that local sources, such as agricultural uses of fungicides, may have led to elevated mercury levels two to three decades ago.[46] Similar trends have been noted for mercury levels in eggs of the common loon collected from New York and New Hampshire.[47] The downward trend in mercury concentrations observed in the environment in some geographic locations over the last few decades generally corresponds to regional mercury use and consumption patterns over the same time frame (consumption patterns are discussed in Volume II of the *Mercury Study Report to Congress*).[20]

7.1.2 Atmospheric Processes

Basic processes involved in the atmospheric fate and transport of mercury include: (1) emissions to the atmosphere; (2) transformation and transport in the atmosphere; (3) deposition from the air; and then (4) re-emission to the atmosphere. Each of these processes is briefly described below.

7.1.2.1 Emissions of Mercury. As discussed fully in Volume II of the *Mercury Study Report to Congress*,[20] mercury is emitted to the atmosphere through both naturally occurring and anthropogenic processes. Natural processes include volatilization of mercury in marine and aquatic environments, volatilization from vegetation, degassing of geologic materials (e.g., soils), and volcanic emissions. The natural emissions are thought to be primarily in the elemental mercury form. Conceptually, the current natural emissions can arise from two components: mercury present as part of the pre-industrial equilibrium and mercury mobilized from deep geologic deposits and added to the global cycle by human activity.

Anthropogenic mercury releases are thought to be dominated on the national scale by industrial processes and combustion sources that release mercury into the atmosphere. Available information indicates that stack emissions include both gaseous and particulate forms of mercury. Gaseous mercury, Hg(g), emissions are believed to include both elemental and oxidized chemical forms, while particulate mercury, Hg(p), emissions are thought to be composed primarily of oxidized compounds due to the relatively high vapor pressure of Hg(0). The analytic methods for mercury speciation of exit gasses and emission plumes are being refined, and there is still controversy in this field. Chemical reactions occurring in the emission plume are also possible. Available information suggests that the speciation of mercury emissions depend on the fuel used (e.g., coal, oil), flue gas cleaning and operating temperature, and possibly other factors. The exit stream is thought to range from almost all divalent mercury to nearly all elemental mercury. Most of the mercury emitted at the stack outlet is found in the gas phase although exit streams containing soot can bind up some fraction of the mercury. The divalent fraction is split between gaseous and particle bound phases.[28] Much of this Hg(II) is believed to be mercuric chloride ($HgCl_2$).[48]

An emission factor-based approach was used to develop the nationwide emission estimates for the fossil fuel combustion categories presented in Table 7-1. The emission factors presented are estimates based on ratios of mass mercury emissions to measures of source activities and nationwide source activity levels. The reader should note that the data presented in this table are estimates; uncertainties include the precision of measurement techniques and the calculation of emission factors, estimates of pollutant control efficiency, and nationwide source class activity levels. The estimates may also be based on limited information for a particular source class, thereby increasing the uncertainty in the estimate further. Due to these and other uncertainties, other sources have calculated different total emissions estimates using similar methods.[49]

7.1.2.2 Transformation and Transport of Atmospheric Mercury. Hg(0) has an atmospheric residence time of about one year and will thus be distributed fairly evenly in the troposphere. Oxidized mercury may be deposited relatively quickly if it is precipitated out, leading to a residence time of hours to months. Longer residence times are possible as well; the atmospheric residence time for some Hg(II) associated with fine particles may approach one year.[49]

The transformation of Hg(0)(g) to Hg(II)(aqueous) and Hg(II)(p) in cloud water demonstrates a possible mechanism by which natural and anthropogenic sources of Hg(0) to air can result in mercury deposition to land and water. This deposition can occur far from the source due to the slow rate of Hg(0)(g) uptake in cloud water. It has been suggested that this mechanism is important in a global sense for Hg pollution, while direct wet deposition of anthropogenic Hg(II) is the most important locally.[3,28] Gaseous Hg(II) is expected to deposit at a faster rate after release than particulate Hg(II) assuming that most

Table 7-1. Best Point Estimates of National Mercury Emission Rates by Category

Sources of mercury[a]	1994-1995 Mg/yr[b]	1994-1995 tons/yr[b]	% of Total inventory[b]
Area sources	3.1	3.4	2.2
Lamp breakage	1.4	1.5	1.0
General laboratory use	1.0	1.1	0.7
Dental preparations	0.6	0.7	0.4
Landfills	<0.1	<0.1	0.0
Mobile sources	c	c	c
Paint use	c	c	c
Agricultural burning	c	c	c
Point Sources	140.9	155.7	97.8
Combustion sources	125.2	137.9	86.9
Utility boilers	46.8	51.5	32.6
Coal	(46.7)[d]	51.3	32.5
Oil	(0.2)	(0.2)	(0.1)
Natural gas	(<0.1)	(<0.1)	(0.0)
MWCs[h]	26.9	29.6	18.7
Commercial/industrial boilers	25.8	28.4	17.9
Coal	(18.8)	(20.7)	(13.1)
Oil	(7.0)	(7.7)	(4.9)
MWIs[h]	14.6	16.0	10.1
Hazardous waste combustors[e]	6.4	7.1	4.4
Residential boilers	3.3	3.6	2.3
Oil	(2.9)	(3.2)	(2.0)
Coal	(0.4)	(0.5)	(0.3)
SSIs	0.9	1.0	0.6
Wood-fired boilers[f]	0.2	0.2	0.1
Crematories	<0.1	<0.1	0.0
Manufacturing sources	14.4	15.8	10.0
Chlor-alkali	6.5	7.1	4.5
Portland cement[e]	4.4	4.8	3.1
Pulp and paper manufacturing	1.7	1.9	1.2
Instruments manufacturing	0.5	0.5	0.3
Secondary Hg production	0.4	0.4	0.3
Electrical apparatus	0.3	0.3	0.2
Carbon black	0.3	0.3	0.2
Lime manufacturing	0.1	0.1	0.1
Primary lead	0.1	0.1	0.1
Primary copper	<0.1	<0.1	0.0
Fluorescent lamp recycling	<0.1	<0.1	0.0
Batteries	<0.1	<0.1	0.0
Primary Hg production	c	c	c
Mercury compounds	c	c	c
Byproduct coke	c	c	c
Refineries	c	c	c
Miscellaneous sources	1.3	1.4	0.9
Geothermal power	1.3	1.4	0.9
Turf products	g	g	g
Pigments, oil, etc.	g	g	g
TOTAL	144	158	100

[a] MWC = Municipal waste combustor; MWI = medical waste incinerator; SSI = sewage sludge incinerator.
[b] Numbers do not add exactly because of rounding.
[c] Insufficient information to estimate 1994-1995 emissions.
[d] Parentheses denote subtotal within larger point source category.
[e] For the purpose of this inventory, cement kilns that burn hazardous waste for fuel are counted as hazardous waste combustors.
[f] Includes boilers only; does not include residential wood combustion (wood stoves).
[g] Mercury has been phased out of use.
[h] U.S. EPA has finalized emission guidelines for these source categories which will reduce mercury emissions by at least an additional 90 percent over 1995 levels.

of the particulate matter is less than 1 μm in diameter. An atmospheric residence time of ½ - 2 years for elemental mercury compared to as little as hours for some Hg(II) species is expected.[50] This behavior is observed in the modeling results presented in this effort as well. It is possible that dry deposition of Hg(0) can occur from ozone mediated oxidation of elemental mercury taking place on wet surfaces, but this is not expected to be comparable in magnitude to the cloud droplet mediated processes.

This great disparity in atmospheric residence time between Hg(0) and the other mercury species leads to very much larger scales of transport and deposition for Hg(0). Generally, air emissions of Hg(0) from anthropogenic sources, fluxes of Hg(0) from contaminated soils and water bodies, and natural fluxes of Hg(0) all contribute to a global atmospheric mercury reservoir with a holding time of ½ to 2 years. Global atmospheric circulation systems can take Hg(0) emissions from their point of origin and carry them anywhere on the globe before transformation and deposition occur. Emissions of all other forms of mercury are likely to be deposited to the earth's surface before they thoroughly dilute into the global atmosphere. Continental-scale atmospheric modeling, such as that performed for this study using the Regional Lagrangian Model of Air Pollution (RELMAP), can explicitly simulate the atmospheric lifetime of gaseous and particulate mercury species, but not Hg(0). Although Hg(0) is included as a modeled species in the RELMAP analysis, the vast majority of Hg(0) emitted in the simulation transports outside the spatial model domain without depositing, and the same is generally thought to happen in the real atmosphere. Natural Hg(0) emissions and anthropogenic Hg(0) emissions from outside the model domain are simulated in the form of a constant background Hg(0) concentration of 1.6 ng m^{-3}, approximating conditions observed in remote oceanic regions.[3] This background Hg(0) concentration is subject to simulated wet deposition by the same process as explicitly modeled anthropogenic sources of Hg(0) within the model domain.

Explicit numerical models of global-scale atmospheric mercury transport and deposition have not yet been developed. As the general understanding of the global nature of atmospheric mercury pollution develops, numerical global-scale atmospheric models will surely follow.

7.1.2.3. Deposition of Mercury. The divalent species emitted, either in the vapor or particulate phase, are thought to be subject to much faster atmospheric removal than elemental mercury.[51,52] Both particulate and gaseous divalent mercury is assumed to dry deposit (this is defined as deposition in the absence of precipitation) at significant rates when and where measurable concentrations of these mercury species exist. The deposition velocity of particulate mercury is dependent on atmospheric conditions and particle size. Particulate mercury is also assumed to be subject to wet deposition due to scavenging by cloud microphysics and precipitation. The gaseous divalent mercury emitted is also expected to be scavenged readily by

precipitation. Divalent mercury species have much lower Henry's law constants than elemental mercury, and thus are assumed to partition strongly to the water phase. Dry deposition of gas phase divalent mercury is thought to be significant due to its reactivity with surface material. Overall, gas phase divalent mercury is more rapidly and effectively removed by both dry and wet deposition than particulate divalent mercury,[51,52,53] a result of the reactivity and water solubility of gaseous divalent mercury.

In contrast, elemental mercury vapor is not thought to be susceptible to any major process of direct deposition to the earth's surface due to its relatively high vapor pressure and low water solubility. On non-assimilating surfaces elemental mercury deposition appears negligible,[51] and though elemental mercury can be formed in soil and water due to the reduction of divalent mercury species by various mechanisms, this elemental mercury is expected to volatilize into the atmosphere.[27] In fact, it has been suggested that *in-situ* production and afflux of elemental mercury could provide a buffering role in aqueous systems, as this would limit the amount of divalent mercury available for methylation.[3] Water does contain an amount of dissolved gaseous elemental mercury,[54] but it is minor in comparison to the dissolved-oxidized and particulate mercury content.

There appears to be a potential for deposition of elemental mercury via plant-leaf uptake. Lindberg et al.[51] indicated that forest canopies could accumulate elemental mercury vapor via gas exchange at the leaf surface followed by mercury assimilation in the leaf interior during the daylight hours. This process causes a downward flux of elemental mercury from the atmosphere, resulting in a deposition velocity. Recent evidence[55] indicates that this does occur but only when air concentrations of elemental mercury are above an equilibrium level for the local forest ecosystem. At lower air concentration levels, the forest appears to act as a source of elemental mercury to the atmosphere, with the measured mercury flux in the upward direction. Lindberg et. al.[56] noted this may be explained by the volatilization of elemental mercury from the canopy/soil system, most likely the soil. Hanson et al.[55] stated that "dry foliar surfaces in terrestrial forest landscapes may not be a net sink for atmospheric elemental mercury, but rather as a dynamic exchange surface that can function as a source or sink dependent on current mercury vapor concentrations, leaf temperatures, surface condition (wet versus dry) and level of atmospheric oxidants." Similarly, Mosbaek et al.[57] convincingly showed that most of the mercury in leafy plants is due to air-leaf transfer, but that for a given period of time the amount of elemental mercury released from the plant-soil system greatly exceeds the amount collected from the air by the plants. It is also likely that many plant/soil systems accumulate airborne elemental mercury when air concentrations are higher than the long-term average for the particular location, and release elemental mercury when air concentrations fall below the local long-term average. On regional and global scales, dry deposition of Hg(0) does not appear to be a

significant pathway for removal of atmospheric mercury, although approximately 95 percent or more of atmospheric mercury is Hg(0).[3]

There is an indirect pathway, however, by which elemental mercury vapor released into the atmosphere may be removed and deposited to the earth's surface. Chemical reactions occur in the aqueous phase (cloud droplets) that both oxidize elemental mercury to divalent mercury and reduce the divalent mercury to elemental mercury. The most important reactions in this aqueous reduction-oxidation balance are thought to be oxidation of elemental mercury with ozone, reduction of divalent mercury by sulfite (SO_3^{-2}) ions, or complexation of divalent mercury with soot to form particulate divalent mercury:

$$Hg(0)(g) \rightarrow Hg(0)(aq)$$
$$Hg(0)(aq) + O_3(aq) \rightarrow Hg(II)(aq)$$
$$Hg(II)(aq) + \text{soot/possible evaporation} \rightarrow Hg(II)(p)$$
$$Hg(II)(aq) + SO_3^{-2}(aq) \rightarrow Hg(0)(aq)$$

(g) = gas phase molecule
(aq) = aqueous phase molecule
(p) = particulate phase molecule

The Hg(II) produced from oxidation of Hg(0) by ozone can be reduced back to Hg(0) by sulfite; however, the oxidation of Hg(0) by ozone is a much faster reaction than the reduction of Hg(II) by sulfite. Thus, a steady state concentration of Hg(II)(aq) is built up in the atmosphere and can be expressed as a function of the concentrations of Hg(0)(g), O_3(g), H^+ (representing acids) and SO_2(g).[28] Note that H^+ and SO_2(g), although not apparent in the listed atmospheric reactions, control the formation of sulfite.

The Hg(II)(aq) produced would then be susceptible to atmospheric removal via wet deposition. The third reaction, however, may transform most of the Hg(II)(aq) into the particulate form, due to the much greater amounts of soot than mercury in the atmosphere. The soot concentration will not be limiting compared to the concentration of Hg(II)(aq), and S atoms in the soot matrix will bond readily to the Hg(II)(aq). The resulting Hg(II)(p) can then be removed from the atmosphere by wet deposition (if the particle is still associated with the cloud droplet) or dry deposition (following cloud droplet evaporation). It is possible that dry deposition of Hg(0) can occur from ozone mediated oxidation of elemental mercury taking place on wet surfaces, but this is not expected to be comparable in magnitude to the cloud droplet mediated processes.[58]

Mercury released into the atmosphere from natural and anthropogenic sources deposits mainly as Hg(II), from either direct deposition of emitted Hg(II) or from conversion of emitted elemental Hg(0) to Hg(II) through ozone-mediated reduction. The former process may result in elevated deposition rates around atmospheric emission sources and the latter process results in regional/global transport followed by deposition.

There is still a great deal of uncertainty with respect to the amount of dry deposition of mercury. Once deposited, mercury appears to bind tightly to certain soil components. The deposited Hg(II) may revolatilize through reduction and be released back to the atmosphere as Hg(0). Soil Hg(II) may also be methylated to form methylmercury; these two forms may remain in the soil or be transported through the watershed to a water body via runoff and leaching. Mercury enters the water body through direct deposition on the watershed, and mercury in water bodies has been measured in both the water column and the sediments. Hg(II) in the water body may also be methylated to form methylmercury; both Hg(II) and methylmercury may be reduced to form Hg(0) which is reintroduced to the atmosphere.

7.1.2.4 Re-emissions of Mercury into the Atmosphere. Re-emission of deposited mercury results most significantly from the evasion of elemental mercury from the oceans. In this process, anthropogenically emitted mercury is deposited to the oceans as Hg(II) and then reduced to volatile Hg(0) and re-emitted. According to one estimate, this process accounts for approximately 30 percent (10 Mmol/year) of the total mercury flux to the atmosphere.[39] Overall, 70 to 80 percent of total current mercury emissions may be related to anthropogenic activities.[34] By considering the current global mercury budget and estimates of the preindustrial mercury fluxes, Mason et al.[39] estimate that total emissions have increased by a factor of 4.5 since preindustrial times, which has subsequently increased the atmospheric and oceanic reservoirs by a factor of 3. The difference is attributed to local deposition near anthropogenic sources. Although the estimated residence time of elemental mercury in the atmosphere is about 1 year, the equilibrium between the atmosphere and ocean waters results in a longer time period needed for overall change to take place for reservoir amounts. Therefore, by substantially increasing the size of the oceanic mercury pool, anthropogenic sources have introduced long- term perturbations into the global mercury cycle. Fitzgerald and Mason[34] estimate that if all anthropogenic emissions were stopped, it would take about 15 years for mercury pools in the oceans and the atmosphere to return to pre-industrial conditions. The Science Advisory Board, in its review of the EPA's Mercury Study, concluded that it could take significantly longer. There is scientific agreement, however, that the slow release of mercury from terrestrial sinks to freshwater and coastal waters will persist for a long time, probably decades, which effectively increases the length of time anthropogenic emissions would impact the environment. This is particularly significant given that the surface soils contain most of the pollution-derived mercury of the industrial period. As a result, it is uncertain at this time how long it would take after reductions in anthropogenic emissions for mercury levels in the global environment, including fish levels, to return to true background levels. The slow release of mercury from terrestrial sinks to freshwater and coastal waters will likely persist for much longer, possibly decades, effectively increasing the lifetime of anthropogenic mercury further.[34] This may be particularly significant considering that surface soils currently contain most of the pollution-derived

mercury of the industrial period. Thus, re-emissions of past anthropogenic mercury emissions will contribute to long-term influences on the global biogeochemical cycle for mercury.

7.1.3 Terrestrial and Aquatic Fate of Mercury

7.1.3.1 Mercury in Soil. Once deposited, the Hg(II) species are subject to a wide array of chemical and biological reactions. Soil conditions (e.g., pH, temperature and soil humic content) are typically favorable for the formation of inorganic Hg(II) compounds such as $HgCl_2$, $Hg(OH)_2$ and inorganic Hg(II) compounds complexed with organic anions.[59] Although inorganic Hg(II) compounds are quite soluble (and, thus, theoretically mobile) they form complexes with soil organic matter (mainly fulvic and humic acids) and mineral colloids; the former is the dominating process. This is due largely to the affinity of Hg(II) and its inorganic compounds for sulfur-containing functional groups. This complexing behavior greatly limits the mobility of mercury in soil. Much of the mercury in soil is bound to bulk organic matter and is susceptible to elution in runoff only by being attached to suspended soil or humus. Some Hg(II), however, will be absorbed onto dissolvable organic ligands and other forms of dissolved organic carbon (DOC) and may then partition to runoff in the dissolved phase. Currently, the atmospheric input of mercury to soil is thought to exceed greatly the amount leached from soil, and the amount of mercury partitioning to runoff is considered to be a small fraction of the amount of mercury stored in soil. The affinity of mercury species for soil results in soil acting as a large reservoir for anthropogenic mercury emissions.[60,23] For example, note the mercury budget proposed by Meili et al.[60] Even if anthropogenic emissions were to stop entirely, leaching of mercury from soil would not be expected to diminish for many years.[23] Hg(0) can be formed in soil by reduction of Hg(II) compounds/complexes mediated by humic substances.[25] This Hg(0) will vaporize eventually and re-enter the atmosphere. Methylmercury can be formed by various microbial processes acting on Hg(II) substances. Approximately 1-3 percent of the total mercury in surface soil is methylmercury, and as is the case for Hg(II) species, it will be bound largely to organic matter. The other 97-99 percent of total soil mercury can be considered largely Hg(II) complexes, although a small fraction of Hg in typical soil will be Hg(0).[61]

7.1.3.2 Plant and Animal Uptake of Mercury. While there is a great deal of uncertainty surrounding air-to-plant transfer of mercury, some evidence indicates that this pathway may be an important source of mercury to soils via defoliation. Overall, mercury concentrations in plants, even those whose main uptake appears to be from the air, are expected from modeling results to be low. This prediction is corroborated by low reported mercury concentrations in most green plants, although the data set of these values is not complete and there are some exceptions. The bulk of the mercury in plants appears to be inorganic.[50] Livestock typically accumulate little mercury from foraging or silage/grain consumption, and the mercury content of meat is low. Due to these factors, the terrestrial

pathway is not expected to be significant, particularly when compared to the consumption of fish by humans. Since this is not an exposure pathway of concern for mercury, it was not included in the modeling that follows.

7.1.3.3 Mercury in the Freshwater Ecosystem. There are a number of pathways by which mercury can enter the freshwater environment: Hg(II) and methylmercury from atmospheric deposition (wet and dry) can enter water bodies directly; Hg(II) and methylmercury can be transported to water bodies in runoff (bound to suspended soil/humus or attached to dissolved organic carbon); and Hg(II) and methylmercury can leach into the water body from groundwater flow in the upper soil layers. Once in the freshwater system, the same complexation and transformation processes that occur to mercury species in soil will occur in aquatic media along with additional processes due to the aqueous environment. Mercury concentrations are typically reported for particular segments of the water environment; the most common of these are the water column (further partitioned as dissolved or attached to suspended material), the underlying sediment (further divided into surface sediments and deep sediments), and biota (particularly fish).

Most of the mercury in the water column, Hg(II) and methylmercury, will be bound to organic matter, either to dissolved organic carbon[62,28] or to suspended particulate matter. In most cases, studies that refer to the dissolved mercury in water include mercury complexes with DOC. Studies indicate that about 25-60 percent of Hg(II) and methylmercury organic complexes are particle-bound in the water column. The rest is in the dissolved, bound-to-DOC phase.[25,63] Hg(0) is produced in fresh water by humic acid reduction of Hg(II) or demethylation of methylmercury. Some will remain in the dissolved gaseous state, but most will volatilize. As noted previously, Hg(0) constitutes very little of the total mercury in the water column but may provide a significant pathway for the evolution of mercury out of the water body via Hg(II) or methylmercury -> Hg(0) -> volatilization. For many lakes, however, sedimentation of the Hg(II) and methylmercury bound to particulate matter is expected to be the dominant process for removal of mercury from the water column.[24]

Generally, no more than 25 percent of the total mercury in a water column exists as a methylmercury complex; typically, less than 10 percent is observed. This is a result of methylation of Hg(II) which is thought to occur in the bottom sediment and the water column by microbial action and abiotic processes. An equilibrium is soon established between Hg(II) and methylmercury in freshwater systems; in a number of sediment-water systems, it has been found that methylmercury concentrations in waters were independent of water column residence time or time in contact with sediments.[64] Methylmercury in the water column which is lost through demethylation, exported downstream, or taken up by biota is thought to be replaced by additional methylation of Hg(II) compounds to sustain equilibrium.

Once entering a water body, mercury can remain in the water column, be lost from the lake through drainage water, revolatilize into the atmosphere, settle into the sediment or be taken up by aquatic biota. After entry, the movements of mercury through any specific water body may be unique. Only mercury in the water column, the sediment, and other aquatic biota appears to be available to aquatic organisms for uptake.

Methylation appears to be a key step in the entrance of mercury into the food chain.[24] The biotransformation of inorganic mercury species to methylated organic species in water bodies can occur in the sediment and the water column. Abiotic processes (e.g., humic and fulvic acids in solution) also appear to methylate the mercuric ion. All mercury compounds entering an aquatic ecosystem are not methylated, and demethylation reactions as well as volatilization of dimethylmercury decrease the amount of methylmercury available in the aquatic environment. It is clear that there is a large degree of scientific uncertainty and variability among water bodies concerning the processes that methylate mercury.[24]

Methylmercury is very bioavailable and accumulates in fish through the aquatic food web; nearly 100 percent of the mercury found in fish muscle tissue is methylated.[24] Methylmercury appears to be primarily passed to planktivorous and piscivorous fish via their diets. Larger, longer-lived fish species at the upper end of the food web typically have the highest concentrations of methylmercury in a given water body. Most of the total methylmercury production ends up in biota, particularly fish. Overall, methylmercury production and accumulation in the freshwater ecosystem places this pollutant into a position to be ingested by fish-eating organisms.

Methylmercury appears to be efficiently passed through the aquatic food web to the highest trophic level consumers in the community (e.g., piscivorous fish). At this point it can be contacted by fish-consuming humans through ingestion. Methylmercury appears to pass from the human gastrointestinal tract into the bloodstream more efficiently than the divalent species.

7.1.3.4 Fate of Mercury in Marine Environments. As noted earlier, mercury is an atmophillic element and, as such, its global transport occurs primarily through the atmosphere. Elemental mercury, the principle species found in the atmosphere, has a high vapor pressure and a low solubility in water. As a result of these properties, the half-life of atmospheric mercury is thought to be a year or longer. Elemental mercury appears to be deposited to ocean waters primarily through wet deposition. Oxidizing reactions in the atmosphere may also play a role in the conversion of elemental mercury to more reactive atmospheric species which are subsequently deposited.

Mercury found in ocean waters and sediments comprises a large reservoir of the total mercury on the planet. The conceptualization of oceans as reservoirs of mercury is fitting for they serve both as

sources of mercury to the atmosphere and as environmental mercury sinks.[65,66,67] The forms and species of mercury present in the ocean waters and sediments may be transformed as a result of both biotic and abiotic factors within the ocean. The most significant species of mercury from a human health perspective is monomethylmercury (MHg). MHg shows strong evidence of bioaccumulation and biomagnification in the marine food web, potentially posing risks to consumer species (particularly apex marine predators and piscivores).[24]

7.2 MERCURY HEALTH EFFECTS

A brief summary of the health effects of methylmercury is presented here. The 1997 EPA *Mercury Study Report to Congress*[68] contains more information on the health effects of mercury and mercury compounds.

Most of the population of the earth have some exposure to mercury as a result of normal daily activities. The general population may be exposed to mercury through inhalation of ambient air; consumption of contaminated food, water, or soil; and/or dermal exposure to substances containing mercury. In addition, some quantity of mercury is released from dental amalgam.

The health effects literature contains many investigations of populations with potentially high exposure to mercury, including industrial workers, people living near point sources of mercury emissions, people who consume large amounts of fish, and dental professionals. There also are numerous studies of populations exposed to high levels of mercury, such as the Minamata poisoning episode in Japan. Volume IV of the EPA's *Mercury Study Report to Congress*[69] presents measured and predicted mercury exposure for various U.S. populations.

The form of mercury which is emphasized here is methylmercury because methylmercury is the form of primary interest for human exposures for this report. It is acknowledged that humans can be exposed to elemental and inorganic mercury and that certain populations can be exposed to many types of organic mercurials, such as antiseptics and pesticides, which are not discussed here.

7.2.1 Toxicokinetics

The toxicokinetics (i.e., absorption, distribution, metabolism, and excretion) of mercury is highly dependent on the form of mercury to which a receptor has been exposed. Below is a brief summary of the toxicokinetics information for methylmercury.

Methylmercury is rapidly and extensively absorbed through the gastrointestinal tract. Absorption information following inhalation exposures is limited. This form of mercury is distributed throughout the body and easily penetrates the blood-brain and placental barriers in humans and animals. Methylmercury transport into tissues appears to be mediated by the formation of a methylmercury-cysteine complex.

This complex is structurally similar to methionine and is transported into cells via a widely distributed neutral amino acid carrier protein. Methylmercury in the body is considered to be relatively stable and is only slowly demethylated to form mercuric mercury in rats. It is hypothesized that methylmercury metabolism may be related to a latent or silent period observed in epidemiological studies observed as a delay in the onset of specific adverse effects. Methylmercury has a relatively long biological half-life in humans; estimates range from 44 to 80 days. Excretion occurs via the feces, breast milk, and urine.

7.2.2 Biological Effects

The primary targets for toxicity of mercury and mercury compounds are the nervous system, kidney, and developing fetus. Other systems that may be affected include the respiratory, cardiovascular, gastrointestinal, hematologic, immune, and reproductive systems. A brief summary of the biological effects of methylmercury is presented here.

Three human studies that examined the relationship between methylmercury and cancer incidence were considered extremely limited because of study design inappropriate for risk assessment or incomplete data reporting. Evidence from animal studies provides limited evidence of carcinogenicity. Male ICR and B6C3F1 mice exposed orally to methylmercuric chloride were observed to have an increased incidence of renal adenomas, adenocarcinomas, and carcinomas. Renal epithelial cell hyperplasia and tumors, however, were observed only in the presence of profound nephrotoxicity suggesting that the tumors may be a consequence of reparative changes to the damaged kidneys. Tumors were observed at a single site, in a single species and sex.

Methylmercury appears to be clastogenic but not a potent mutagen. Studies have also shown evidence that methylmercury may induce mammalian germ cell chromosome aberrations. There are a number of studies in both humans and experimental animals that show methylmercury to be a developmental toxicant. Neurotoxicity in offspring is the most commonly observed effect and the effect seen at lowest exposures.

A significant body of human studies exists for evaluating the potential systemic toxicity of methylmercury. This data base is the result of studying two large scale poisoning episodes in Japan and Iraq as well as several epidemiological studies assessing populations that consume significant quantities of fish. In addition, much research on the toxicity of methylmercury has been conducted in animals including non-human primates.

The critical target for methylmercury toxicity is the nervous system. The developing fetus may be at particular risk from methylmercury exposure. Offspring born of women exposed to high doses of methylmercury during pregnancy have exhibited a variety of developmental neurological abnormalities, including the following:

delayed onset of walking, delayed onset of talking, cerebral palsy, altered muscle tone and deep tendon reflexes, and reduced neurological test scores. Maternal toxicity may or may not have been present during pregnancy for those offspring exhibiting adverse effects. For the general population, the critical effects observed following methylmercury exposure are multiple central nervous system effects including ataxia and paresthesia.

A latent or silent period has been observed in some epidemiological and animal studies indicating a delay in the onset of adverse effects. It is hypothesized this delay may be related to methylmercury metabolism.

7.2.3 Sensitive Subpopulations

A susceptible population is a group that may experience more severe adverse effects at comparable exposure levels or adverse effects at lower exposure levels than the general population. The greater response of these sensitive subpopulations may be a result of a variety of intrinsic or extrinsic factors. For mercury, the most sensitive subpopulations may be developing organisms. Data are also available indicating that other factors may be associated with the identification of sensitive subpopulations including the following: age; gender; dietary insufficiencies of zinc, glutathione, or antioxidants; predisposition for autoimmune glomerulonephritis; and predisposition for acrodynia.

7.2.4 Interactions

There are data demonstrating that a number of substances affect the pharmacokinetics and/or toxicity of mercury compounds. Of most interest is the potential interaction of selenium and mercury. Selenium is known to bioaccumulate in fish, so exposure to methylmercury from fish consumption may be associated with exposure to increased levels of selenium. There are data indicating that selenium co-administered with methylmercury can form selenium-methylmercury complexes. The formation of these complexes may temporarily prevent methylmercury-induced tissue damage but also may delay excretion of the methylmercury. Thus, formation of selenium-methylmercury complexes may not reduce methylmercury toxicity but rather may delay onset of symptoms. More information is needed to understand the possible interaction of selenium with methylmercury. There is also potential for interaction between various forms of mercury and ethanol, thiol compounds, tellurium, potassium dichromate, zinc, atrazine, and vitamins C and E.

7.2.5 Hazard Identification/Dose-Response Assessment

The available toxicological and epidemiological evidence was evaluated, and U.S. EPA risk assessment guidelines and methodologies were applied to hazard identification for various endpoints; namely, carcinogenicity, germ cell mutagenicity, developmental toxicity, and

general systemic toxicity. Data supported quantitative assessments of systemic toxicity. An oral reference dose (RfD[a]) was calculated for methylmercury. U.S. EPA derived the RfD for methylmercury by extrapolating from the high-dose exposures that occurred in the Iraq incident. Data for carcinogenicity of inorganic and methylmercury were judged to be inadequate in humans and limited from animal bioassays. The carcinogenicity data for methylmercury were not sufficient to support a quantitative assessment. Table 7-2 summarizes the hazard identification and dose-response information for organic mercury.

7.2.6 Ongoing Research

While much data has been collected on the potential toxicity of mercury and mercury compounds, much is still unknown. Two ongoing epidemiological studies are now providing critical information on the developmental toxicity of methylmercury. One study, being conducted in the Seychelles Islands, is evaluating dose-response relationships in a human population with dietary exposures (fish) at levels believed to be in the range of the threshold for developmental toxicity. The second study, conducted in the Faroe Islands, is assessing mercury exposure in a population that consumes a relatively large quantity of marine fish and marine mammals. Children exposed to methylmercury *in utero* and followed through 6 years of age have been assessed for mercury exposure and neurological developmental. Because of various limitations and uncertainties in all of the available data, the U.S. EPA and other Federal agencies intend to participate in an interagency review of the human data on methylmercury, including the most recent studies from the Seychelle Islands and the Faroe Islands. The purposes of this review are to refine the estimates of the level of exposure to mercury associated with subtle neurological endpoints and to further consensus among all of the Federal agencies. After this process, the U.S. EPA will determine if a change in the RfD for methylmercury is warranted.

7.2.7 Research Needs

Specifically, information is needed to reduce the uncertainties associated with the current oral RfD for methylmercury. More work with respect to both dose and duration of exposure would also allow for potentially assessing effects above the RfD. Limited evidence suggests that methylmercury is a possible human carcinogen. Research on mode of action in induction of tumors at high doses will be of particular use in defining the nature of the dose response relationship for carcinogenicity.

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[a] The oral RfD is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subpopulations) that is likely to be without an appreciable risk of deleterious health effects during a lifetime.

Table 7-2. Summary of U.S. EPA Hazard Identification/Dose-Response Assessment for Methylmercury

Form of mercury	Oral RfD (mg/kg-day)	Inhalation RfC (mg/m^3)	Cancer weight-of-evidence rating	Cancer slope factor	Germ cell mutagenicity	Developmental toxicity data base characterization
Organic	0.0001[a] (methyl-mercury)	n/a	C, possible human carcinogen	n/a	High weight of evidence	Sufficient human and animal data

[a] Critical effect is neurological toxicity in progeny of exposed women, RfD calculated using a benchmark dose (10%).

There are many uncertainties associated with the health effects data analysis, due to an incomplete understanding of the toxicity of methylmercury. The sources of uncertainty include the following:

- The data serving as the basis for the methylmercury RfD were from a population ingesting contaminated seed grain. The nutritional status of this group may not be similar to that of U.S. populations. The exposure was for a short, albeit critical, period of time. It is likely that there is a range of response among individuals to methylmercury exposure. The selenium status of the exposed Iraqi population is not certain, nor is it established the extent to which selenium has an effect on mercury toxicity.

- There was no NOAEL (no-observable-adverse-effect level) for estimation of a threshold for all developmental endpoints. A benchmark was estimated using a Weibull model on grouped data. Use of an estimate other than the 95 percent lower limit on 10 percent response provides alternate estimates. Other modeling approaches using data which have not been grouped provide similar estimates. Benchmark doses, NOAELs, and LOAELs from other human studies provide support for the benchmark used in the RfD.

- Ingestion levels of methylmercury associated with measured mercury in hair were estimated based on pharmacokinetic parameters derived from evaluation of the extant literature. Use of other plausible values for these parameters results in (relatively small) changes in the exposure estimate.

- While there are data to show that the developing fetus is more susceptible to methylmercury toxicity than adults, there are not sufficient data to support calculation of a separate RfD for children (vs. adults).

To improve the risk assessment for methylmercury, U.S. EPA would need the following:

- Results from ongoing studies in human populations with measurable exposure to methylmercury, and new research on actual consumption patterns and estimated methylmercury exposure of the subpopulations of concern, with validation by analysis of hair samples from a representative sample of members of this subpopulation.

- Reproductive studies and analysis.

- Data on mode of action of methylmercury tumor induction.

- Validated physiologically-based pharmacokinetic models for mercury which include a fetal component.

Based on the extant data and knowledge of developing studies, the following outcome can be expected:

- Human populations exposed to sufficiently high levels of methylmercury either *in utero* or *post partum* will have increased incidence of neurotoxic effects.

7.3 MERCURY CONCENTRATIONS IN BIOTA

The *Mercury Study Report to Congress* documents many concentrations in animals and plants.[24] Concentrations in abiotic environmental components consist primarily of inorganic species. While these concentrations may be elevated in specific areas, fish concentrations are generally of highest concern when assessing risks posed by emitted mercury. The concern stems from the consumption of fish by humans and the form of mercury, methylmercury, which fish bioaccumulate. Methylmercury, which is the primary form of mercury found in fish tissue, is a human neurotoxin and is readily absorbed into the human body through the gastrointestinal tract. Fish methylmercury concentrations result from existing environmental concentrations of mercury (which may consist of mercury from anthropogenic and natural sources, as well as mercury which has been re-emitted from the oceans or soils) and deposition from the global reservoir (which includes mercury emitted by other countries).

Given the current scientific understanding of the environmental fate and transport of this element, it is not possible to quantify how much of the methylmercury in fish consumed by the U.S. population is contributed by U.S. emissions relative to other sources of mercury (such as natural sources and re-emissions from the global pool). As a result, it cannot be assumed that a change in total mercury emissions will be linearly related to any resulting change in methylmercury in fish, nor over what time period these changes would occur. This is an area of ongoing study.

7.4 MEASUREMENT DATA NEAR UTILITIES

The measured mercury concentrations in environmental media around utilities are briefly summarized in this section. These data are not derived from a comprehensive study of mercury around utilities. Despite the need for this effort, such a study does not appear to exist. The quality of the following studies has not been assessed by the U.S. EPA. The data do not appear to be directly comparable among themselves because of differences in analytic techniques and collection methods used. Some of these studies are from older literature and may not reflect current mercury emissions from the sources described.

Anderson and Smith[70] measured mercury levels in environmental media and biota around a 200-MW coal-fired utility in Illinois. The facility had two 152-m-high smokestacks and was equipped with an electrostatic precipitator. Commercial operations at the facility had been ongoing for 6 years when sampling was conducted (from 1973 through 1974). Levels of mercury detected in atmospheric particulate samples collected 4.8 and 9.6 km downwind of the facility were not statistically significantly elevated when compared with samples collected 4.8 km upwind of the site. Mercury levels detected in samples from the upper 2 cm of downwind agricultural soils (sample mean 0.022 ppm mercury) were statistically significantly elevated when compared with upwind samples (0.015 ppm mercury). Core sediment sampling from a nearby lake bed showed statistically significant elevations in sediment mercury concentrations after plant operations began (sample mean 0.049 ppm mercury) when compared with sediment deposits prior to operation (0.037 ppm mercury). No increases were observed in mercury levels in fish from the nearby lake when compared with fish from remote lakes.

Crockett and Kinnison[71] sampled the arid soils around a 2,150-MW coal-fired utility in New Mexico in 1974. The four-stack (two stacks 76 m high and two 91 m high) facility had been operational since 1963 and had an estimated mercury release rate of 850 kg/yr. The rainfall in the area averaged 15 to 20 cm/yr. Although a mercury distribution pattern was noted, soil mercury levels near the facility did not differ significantly from background. Given the high amounts of mercury released by the facility and the insignificant amounts detected, the authors speculated that much of the mercury emitted was transported over a larger area, rather than deposited locally. Measurement data near other types of anthropogenic sources are discussed in the 1997 EPA *Mercury Study Report to Congress*.[24]

7.5 MODEL FRAMEWORK

This section describes the models and modeling scenarios used to predict the environmental fate of mercury. Measured mercury concentrations in environmental media were used when available to parameterize these models. Human exposures to mercury were predicted based on modeling results.

7.5.1 Models Used

The extant measured mercury data alone were judged insufficient for a national assessment of mercury exposure for humans from utility units. Thus, the decision was made to model the mercury emissions. In this study, there were three major types of modeling efforts: (1) modeling of mercury atmospheric transport on a regional basis; (2) modeling of mercury atmospheric transport on a local scale (within 50 km of source); and (3) modeling of mercury fate in soils and water bodies into biota, as well as the resulting exposures to human fish consumers. The models used are described in Table 7-3.

7.5.2 Modeling of Long-Range Fate and Transport of Mercury

The goal of this analysis was to model the emission, transport, and fate of airborne mercury over the continental United States using the meteorologic data for the year of 1989 and the most current utility mercury emissions data. The results of the simulation were intended to be used to answer a number of fundamental questions. Probably the most general question was "How much mercury emitted by utility boilers is deposited back to United States soils and water bodies over a typical year?" It is known that year-to-year variations in accumulated precipitation and wind flow patterns affect the observed quantity of mercury deposited to the surface at any given location. Meteorological data for the year 1989 was used since most of the continental United States experienced near average weather conditions during that year. To estimate the quantity of mercury emitted by utilities that deposits in the United States, and specifically which geographic regions may be more highly impacted, information on chemical and physical forms of the mercury emissions was needed since these characteristics determine the rate and location of the wet and dry deposition processes for mercury.

The RELMAP model was used to predict the average annual atmospheric mercury concentration and the wet and dry deposition flux for each ½ degree longitude by ⅓ degree latitude grid cell (approximately 40 km square) in the continental United States. The emission, transport, and fate of airborne mercury over the continental United States was modeled using meteorological data for the year 1989. The utility emission data used were those presented in the *Mercury Study Report to Congress*.[20] Emission data are shown in Table 7-4.

The RELMAP model was originally developed to estimate concentrations of sulfur and sulfur compounds in the atmosphere and rainwater in the eastern United States. The primary modification of RELMAP was the handling of three species of mercury (elemental, divalent, and particulate) and carbon soot (or total carbon aerosol).[24] A complete description of the RELMAP mercury model is presented in the *Mercury Study Report to Congress*.[24] The results of the RELMAP modeling are shown in Figures 7-2 through 7-4.

Table 7-3. Models Used to Predict Mercury Air Concentrations, Deposition Fluxes, and Environmental Concentrations

Model	Description
RELMAP	Predicts average annual atmospheric mercury concentration and wet and dry deposition flux for each 40 km^2 grid in the U.S. due to all anthropocentric sources of mercury in the U.S.
ISC3	Predicts annual average atmospheric concentrations and deposition fluxes within 50 km of mercury emission source
IEM-2M	Predicts environmental mercury concentrations based on air concentrations and deposition rates to watershed and water body. Predicts human exposure based on these predicted concentrations and human activity patterns.

RELMAP = Regional Lagrangian Model of Air Pollution
IEM = Indirect exposure methodology
ISC = Industrial Source Complex

Table 7-4. Mercury Emissions Inventory Used in the RELMAP Modeling (Based on the 1994-95 Estimates)

Mercury emission source type	Emissions (kg/yr)	Assumed speciation percentages		
		Hg(0) [a]	Hg^{2+} [b]	Hg_P [c]
Electric utility boilers (coal, oil and gas)	46,183	50	30	20

[a] Hg(0) represents elemental mercury gas
[b] Hg^{2+} represents divalent mercury gas
[c] Hg_P represents particulate mercury

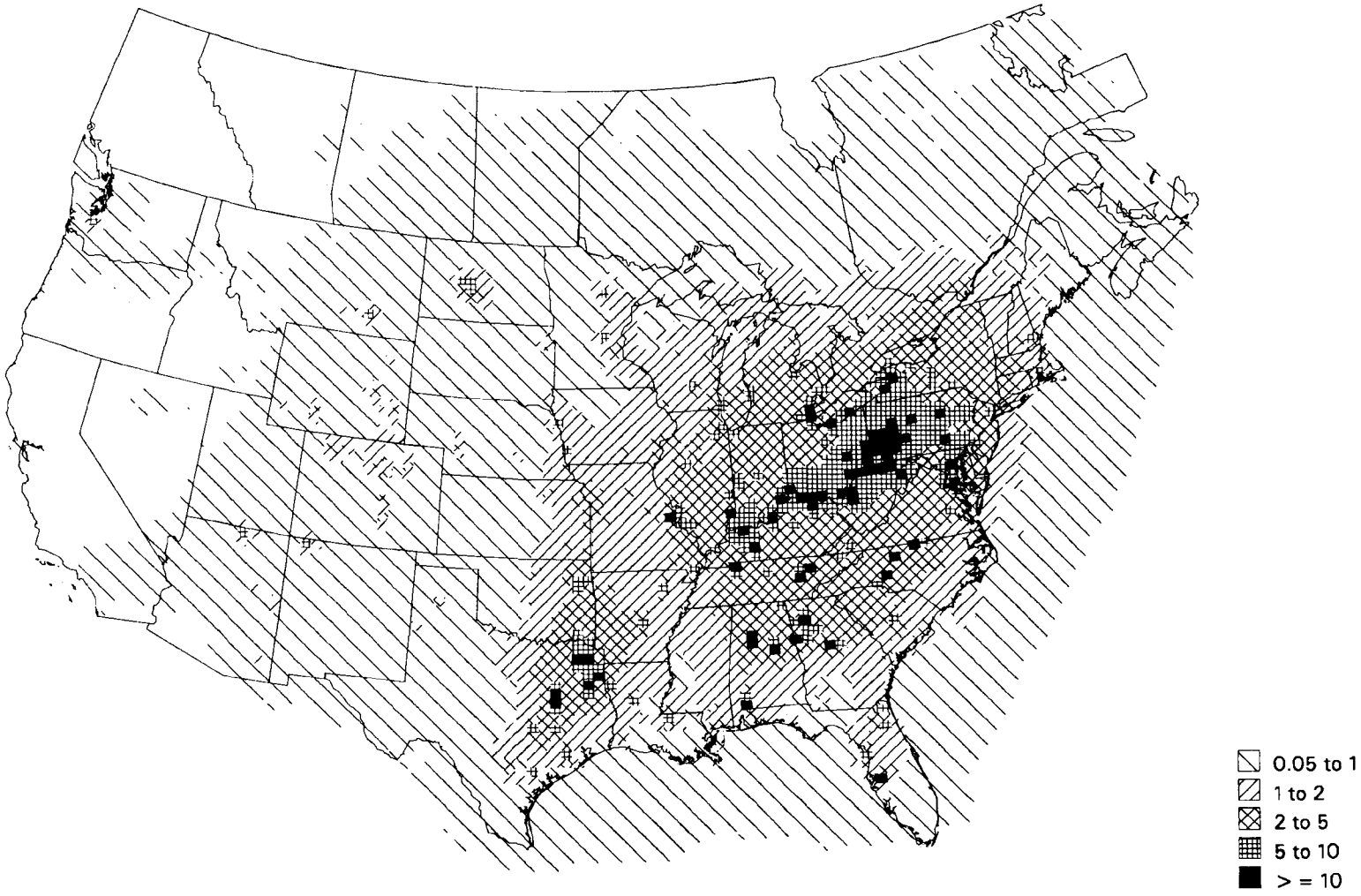


Figure 7-2. Total Modeled Mercury Deposits from Wet and Dry Deposition from Coal Utilities Based on 1994 Emissions Estimates as Modeled with RELMAP, Units: $\mu g/m^2/yr$

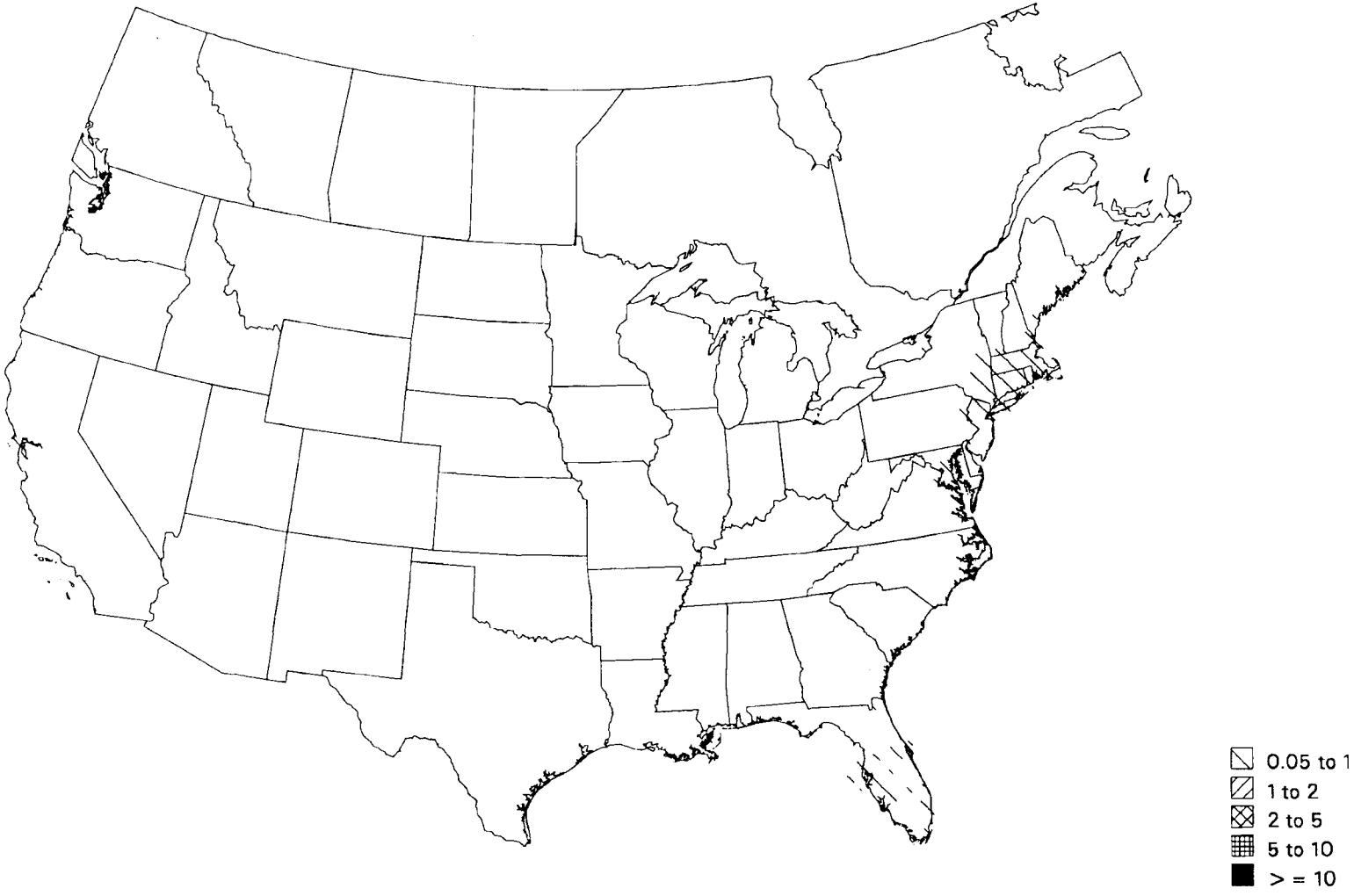


Figure 7-3. Total Modeled Mercury Deposits from Wet and Dry Deposition from Oil Utilities Based on 1994 Emissions Estimates as Modeled with RELMAP, Units: $\mu g/m^2/yr$

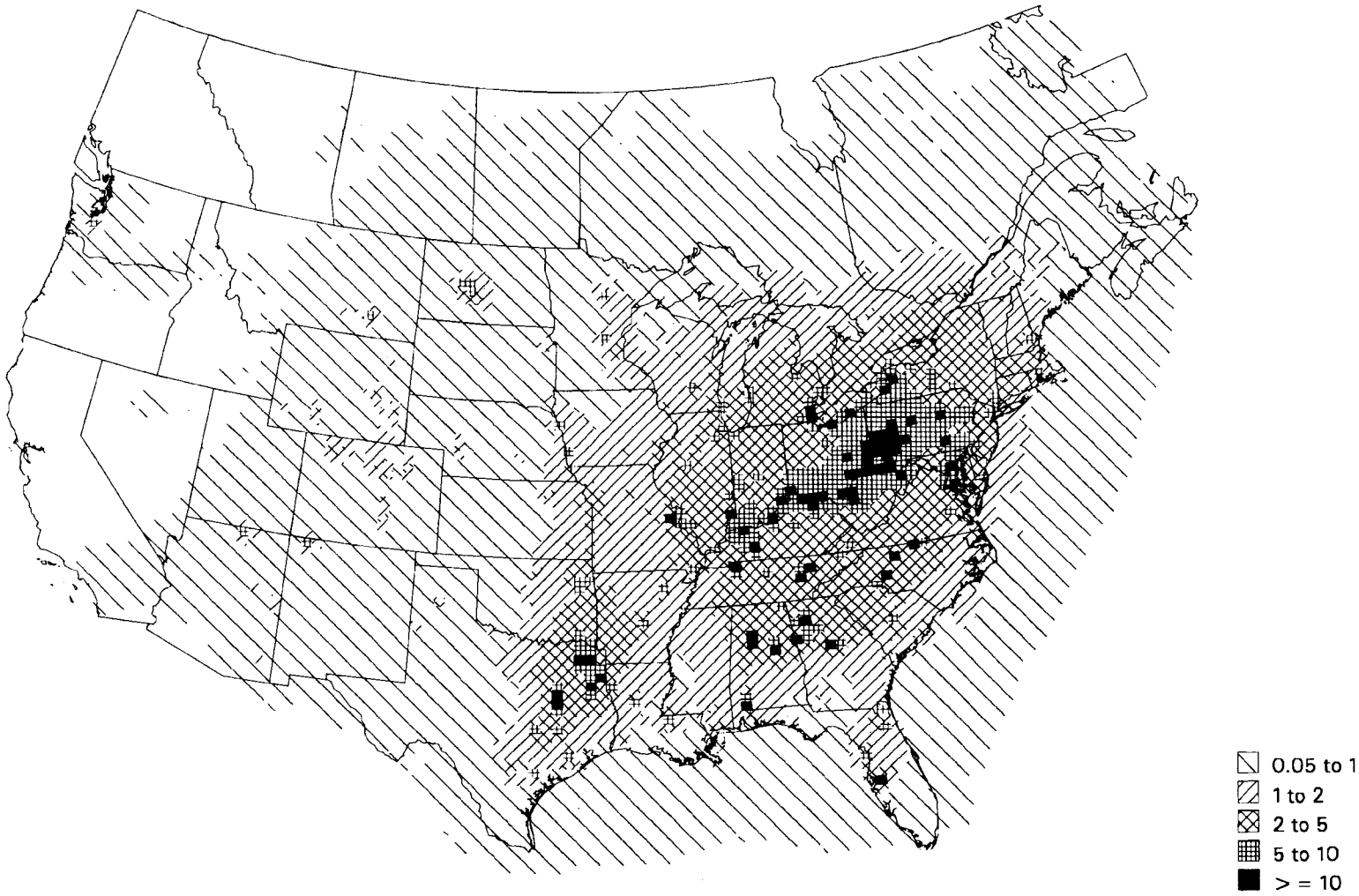


Figure 7-4. Total Modeled Mercury Deposits from Wet and Dry Deposition from Coal and Oil Utilities Based on 1994 Emissions Estimates as Modeled with RELMAP, Units: $\mu g/m^2/yr$

A computer simulation of long-range transport of mercury emissions from all United States sources conducted for the EPA's 1997 Mercury Study Report to Congress suggests that about one-third (~ 52 tons) of the 158 tpy of United States anthropogenic emissions are deposited, through wet and dry deposition, within the lower 48 States. The remaining two-thirds (~ 107 tons) is transported outside of United States borders where it diffuses into the global reservoir. In addition, the computer simulation suggests that another 35 tons of mercury from the global reservoir is deposited for a total deposition of roughly 87 tons. Although this type of modeling is uncertain, the simulation suggests that about three times as much mercury is being added to the global reservoir from United States sources as is being deposited from it. What is not uncertain is that additional emissions to air will contribute to levels in the global reservoir, and concomitant deposition to water bodies.

Long-range transport modeling conducted as part of this Utility Study predicts that approximately 30 percent (i.e., 15 tpy) of the utility mercury emissions deposit in the continental United States. The estimated annual deposition rates resulting from utility mercury emissions range from 0.5 to greater than 10 μg per square meter.

7.5.3 Modeling the Local Transport of Mercury in the Atmosphere

The program used to model the transport of the anthropogenic mercury within 50km of an emissions source was the Industrial Source Complex Version 3 (ISC3) gas deposition model obtained from the United States EPA's Support Center for Regulatory Air Models (SCRAM) website (the program is called GDISCDFT). This model has a gas dry deposition model that was applied in this study. The issues related to using this program to model emitted mercury in the local atmosphere are detailed in Volume III of the *Mercury Study Report to Congress*.[24]

The phase and oxidation state of emitted mercury is thought to be of critical importance in determining atmospheric fate. Only Hg(0) and Hg^{+2} were considered in the air dispersion modeling. At the point of stack emission and during atmospheric transport, the contaminant is partitioned between two physical phases: vapor and particle-bound. It was assumed that 25 percent of the divalent emissions from an individual source would attach to particles in the plume; particle sizes were assumed to reflect ambient particle data.

7.5.3.1 Development and Description of Model Plants. Model plants representing four utility boilers were developed to represent a range of mercury emissions from this source. Parameters for each model plant were selected after evaluation of the characteristics of a given source category and current knowledge of mercury emissions from that source category. Important variables for the mercury risk assessment included mercury emission rates, mercury speciation, and mercury transport/deposition rates. Important model plant parameters included stack height, stack diameter, stack volumetric flow rate, stack gas temperature, plant capacity factor (relative average operating hours per year), stack mercury concentration, and mercury

speciation (see Table 7-5). Emission estimates were assumed to represent typical emission levels emitted from existing sources.[20,24]

7.5.3.2. Hypothetical Locations of Model Plants. There are a variety of geographic aspects that can influence the dispersion of mercury emissions from a utility boiler. These aspects include factors that affect the environmental chemistry of a pollutant and the physics of plume dispersion. Environmental chemistry can include factors such as the amount of wet deposition in a given area. Factors affecting plume dispersion include terrain, wind direction and average wind speed.

Because wet deposition may be an important factor leading to mercury exposures, especially for the more soluble species emitted, the meteorology of a location was used as a selection criterion. Two different types of meteorology were deemed necessary to characterize the environmental fate and transport of mercury: an arid/semi-arid site and a humid site. The criterion specifically utilized was total yearly rainfall. (See Volume III of the *Mercury Study Report to Congress* for details.)[24]

Terrain features refer to the variability of the receptor height with respect to a local source. Two main types of terrain were used in the modeling: simple, and complex. Simple terrain is defined as a study area that is relatively level and well below stack top (rather, the effective stack height). Complex terrain refers to terrain that is not simple, such as source located in a valley or a source located near a hill. This included receptors that are above or below the top of the stack of the source. Complex terrain can affect concentrations, plume trajectory, and deposition. Due to the complicated nature of plume flow in complex terrain, it is probably not possible to predict impacts in complex terrain as accurately as for simple terrain. In view of the wide range of uncertainty inherent in accurately modeling the deposition of the mercury species considered, the impacts posed by complex terrain were not incorporated in the local scale analysis.

Two generic sites are considered: a humid site east of 90 degrees west longitude, and a more arid site west of 90 degrees west longitude (these are described in Volume III of the *Mercury Study Report to Congress*).[24] The primary differences between the two sites as parameterized were the assumed erosion characteristics for the watershed and the amount of dilution flow from the water body. The eastern site had generally steeper terrain in the watershed than the other site. A circular drainage lake with a diameter of 1.78 km and average depth of 5 m, with a 2 cm benthic sediment depth, was modeled at both sites. The watershed area was 37.3 km^2.

7.5.4 Modeling Mercury in a Watershed

Atmospheric mercury concentrations and deposition rates estimated from RELMAP and ISC3 drive the calculations of mercury in watershed soils and surface waters. The soil and water concentrations, in turn,

Table 7-5. Process Parameters for Model Plants

Model plant	Plant size	Capacity (% of year)	Stack height (ft)	Stack diameter (ft)	Hg emission rate (kg/yr)	Speciation percent ($Hg(0)/Hg^{2+}/Hg^{P}$)	Exit velocity (m/sec)	Exit temperature (°F)
Large coal-fired utility boiler	975 Megawatts	65%	732	27	230	50/30/20	31.1	273
Medium coal-fired utility boiler	375 Megawatts	65%	465	18	90	50/30/20	26.7	275
Small coal-fired utility boiler	100 Megawatts	65%	266	12	10	50/30/20	6.6	295
Medium oil-fired utility boiler	285 Megawatts	65%	290	14	2	50/30/20	20.7	322

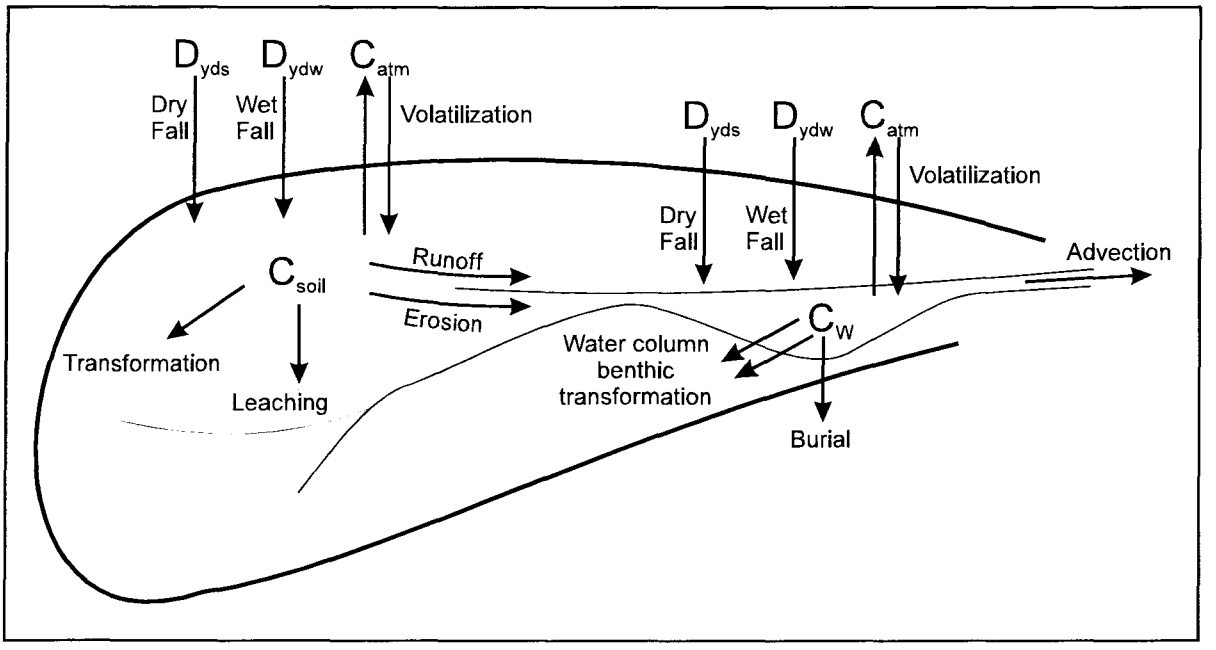
Hg(0) = elemental mercury;
Hg^{2+} = divalent vapor phase mercury;
Hg^{P} = particle-bound mercury

drive calculations of concentrations in the associated biota and fish, which humans are assumed to consume. The watershed model used for this report, Indirect Exposure Methodology Version 2M (IEM-2M), was adapted from the more general IEM-2 methodology[30,31] to handle mercury fate in soils and water bodies. It is described completely in the EPA *Mercury Study Report to Congress*, Volume III.[24]

7.5.4.1 Overview of the Watershed Model. IEM-2M simulates three chemical components: elemental mercury, Hg(0); divalent mercury, HgII; and methylmercury, MHg. In the previous version of IEM-2, these components were assumed to be in a fixed ratio with each other as specified by the fraction elemental (f_1) and fraction methyl (f_3). This version calculates the fractions in each component based on specified or calculated rate constants.

IEM-2M is composed of two integrated modules that simulate mercury fate using mass balance equations describing watershed soils and a shallow lake, as illustrated in Figures 7-5 and 7-6. The mass balances are performed for each mercury component, with internal transformation rates linking Hg(0), HgII, and MHg. Sources include wetfall and dryfall loadings of each component to watershed soils and to the water body. An additional source is diffusion of atmospheric Hg(0) vapor to watershed soils and the water body. Sinks include leaching of each component from watershed soils, burial of each component from lake sediments, volatilization of Hg(0) and MeHg from the soil and water column, and advection of each component out of the lake.

At the core of IEM-2M are nine differential equations describing the mass balance of each mercury component in the surficial soil layer, in the water column, and in the surficial benthic sediments. The equations are solved for a specified interval of time, and predicted concentrations output at fixed intervals. For each



C_{soil}	total mercury concentration in upper soil	ng/g
C_w	total mercury concentration in water body	ng/L
C_{atm}	vapor phase mercury concentration in air	ng/m^3
D_{yds}	average dry deposition to watershed	$\mu g/m^2$-yr
D_{yws}	average wet deposition to watershed	$\mu g/m^2$-yr

Figure 7-5. Overview of the IEM-2M Watershed Modules

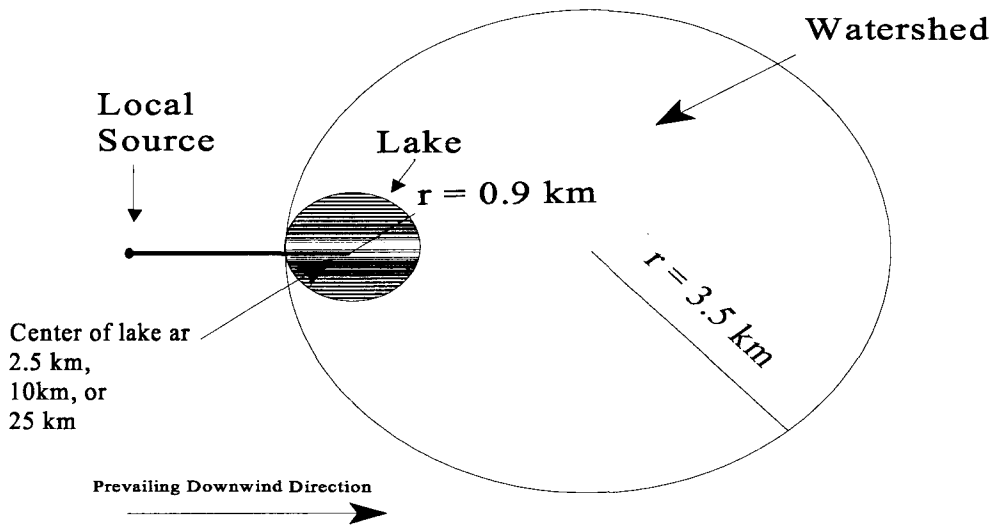


Figure 7-6. Configuration of Hypothetical Water Body and Watershed Relative to Local Source

calculational time step, IEM-2M first performs a terrestrial mass balance to obtain mercury concentrations in watershed soils. Soil concentrations are used along with vapor concentrations and deposition rates to calculate concentrations in various food plants. These are used, in turn, to calculate concentrations in animals. IEM-2M next performs an aquatic mass balance driven by direct atmospheric deposition along with runoff and erosion loads from watershed soils.

The nature of this methodology is basically steady with respect to time and homogeneous with respect to space. While it tracks the buildup of soil and water concentrations over the years given a steady depositional load and long-term average hydrological behavior, it does not respond to unsteady loading or meteorological events. There are limitations on the analysis and interpretations imposed by these simplifications. The model's calculations of average water body concentrations are less reliable for unsteady environments, such as streams, than for more steady environments, such as lakes.[24] The description includes a "benchmarking" exercise with an independent model, the Mercury Cycling Model.

Mhg concentrations in fish are derived from dissolved MHg water concentrations using bioaccumulation factors (BAF).[24] Methylmercury concentrations in fish were derived from predicted water column concentrations of dissolved methylmercury by using BAFs for trophic level 4 fish (Table 7-6). The BAFs selected for these calculations were estimated from existing field data. The BAF (dissolved methylmercury basis) for trophic level 4 fish is 1.6×10^6. Methylmercury was estimated to constitute 7.8 percent of the total dissolved mercury in the water column, and 65 percent of this was assumed to be freely dissolved. The potential variability around these predicted fish residue values is highlighted in Table 7-6, which shows percentile information for the BAF estimates.

There are several limitations to the modeling analyses. First, there is a lack of adequate mercury measurement data near the anthropogenic atmospheric mercury sources considered in this report. To assess how well the modeled data predict actual mercury concentrations in different environmental media at a variety of geographic locations requires a database against which to make these comparisons. The lack of such measured data preclude a comparison of the modeling results with measured data around these sources. These data include measured mercury deposition rates as well as measured concentrations in the atmosphere, soils, water bodies and biota. Substantial additional monitoring data would facilitate such comparison. Second, the IEM-2M has not been validated with site-specific data. The model was benchmarked against the independently-derived Regional Mercury Cycling Model (R-MCM), which itself has been calibrated to several Wisconsin lakes. When driven by the same atmospheric loading and solids concentrations, IEM-2M predictions of mercury concentrations compare well with those calculated by R-MCM for a set of Wisconsin lakes. Additional limitations are discussed in later sections below.

Table 7-6. Percentiles of the Methylmercury Bioaccumulation Factor

Parameter	Percentile of distribution				
	5th	25th	50th	75th	95th
Trophic 4 BAF	3.3×10^6	5.0×10^6	6.8×10^6	9.2×10^6	1.4×10^7

BAF = bioaccumulation factor

7.5.5 Exposure Modeling

7.5.5.1 Description of Hypothetical Human Exposure Scenarios. Human exposure to environmental mercury is the result of mercury concentrations at specific human exposure points (e.g., ingested fish). For each location, mercury exposure was estimated only for individuals representing several specific subpopulations that consumed the freshwater fish that inhabited one of the three local lakes. The individuals representing the subpopulations were defined to model both average and high-end exposures.

The fish ingestion pathway was the only source of methylmercury intake assessed. For this assessment, four human fish consumption scenarios were considered for the hypothetical lakes: (1) an adult subsistence fish consumer who was assumed to ingest large amounts of locally-caught fish; (2) a child of a subsistence local fish consumer; (3) a high-end recreational angler; and 4) an average local fish consumer. These consumption scenarios were thought to represent identified fish-consuming subpopulations in the United States.

Fish for human consumption from local water bodies can be derived from many sources including self-caught, gifts, and grocery and restaurant purchases. For the purposes of this study, all fish consumed were assumed to originate from the hypothetical lakes, which were considered to represent several small lakes that might be present in the type of hypothetical locations considered. No commercial distribution of locally caught fish was assumed; exposure to locally-caught fish was modeled for the fish-consuming subpopulations described above.

Fish consumption rates for the three fish-consuming subpopulations were derived from the Columbia River Inter-Tribal Fish Commission report[72] and the draft EPA *Exposure Factors Handbook*.[73] Other estimates of human fish consumption rates are reported in the *Exposure Factors Handbook*.[73] The estimates presented highlight the broad variability in consumption rates. The Columbia River Inter-Tribal Fish Commission report[72] estimated fish consumption rates for members of four tribes inhabiting the Columbia River Basin. The estimated fish consumption rates were based on interviews with 513 adult tribe members who lived on or near the reservation. The

participants had been selected from patient registrations lists provided by the Indian Health Service. Adults interviewed provided information on fish consumption for themselves and for 204 children under five years of age.

Fish consumption rates for tribal members are shown in Tables 7-7 and 7-8. The values used in this study are shown in Table 7-9. The values listed below reflect an annual average, but monthly variations were also reported. For example, the average daily consumption rate during the two highest intake months was 107.8 g/day, and the daily consumption rate during the two lowest consumption months was 30.7 g/day. Fish were consumed by over 90 percent of the surveyed population, with only 9 percent of the respondents reporting no fish consumption. The maximum daily consumption rate for fish reported by one member of this group was 972 g/day. Since most of the population consisted of fish consumers, utilization of per capita estimates was considered appropriate.

The *Exposure Factors Handbook*[73] describes many freshwater fish consumption studies. The mean daily consumption rates derived for recreational freshwater anglers from the compiled studies range from 5-17 g/day; the derived 95th percentile range was 8-25 g/day. The value of 30 g/day clearly exceeds the 95th percentile; this individual is a high-end consumer. The recommended mean intake for subsistence populations was 70 g/day, and the 95th percentile was 170 g/day. The value of 60 g/day which is used for the subsistence adult is lower than the recommended mean. The body weights used for the adult and child were 70 and 17 kg.[74]

7.6 RESULTS

Tables 7-10 through 7-13 present the results of the multipathway modeling analysis. The results are based on a model plant analysis and are for hypothetical scenarios. Therefore, the results do not apply to any specific utility plant and contain significant uncertainties.

In all cases, the average air concentrations are predicted to be dominated by the regional contribution of utilities rather than the single local source modeled. This is largely due to the high effective stack heights exhibited by the sources. The largest contribution of 35 percent is for the medium coal-fired utility boiler (MCUB) in the western site. The western site is predicted to have lower concentrations of mercury as a result of regional transport.

At both the eastern and western sites using the 50th percentile RELMAP results, the deposition rates, soil concentrations, and fish concentrations are usually dominated by the local coal-fired utility source within 10 km of the source. The small coal-fired utility boiler (SCUB) at the eastern site is the exception due to the higher deposition rate from regional sources. In the eastern site regional sources dominate the deposition rates, soil concentrations, and fish

Table 7-7. Fish Consumption Rates for Columbia River Tribes[72]

Subpopulation	Mean daily fish consumption (g/day)
Total adult population, aged 18 years and older	59
Children, aged 5 years and younger	20
Adult females	56
Adult males	63

Table 7-8. Daily Fish Consumption Rates Among Adults in the Columbia River Tribes[72]

Percentile	g/day
50th	29-32
90th	97-130
95th	170
99th	389

Table 7-9. Fish Consumption Rates Used in This Study

Subpopulation	Fish consumption rate (g/day)[a]
Subsistence adult	60 [a]
High-end child	20 [a]
Recreational angler	8
High-end recreational angler	30 [a]

[a] Columbia River Inter-Tribal Commission, 1994.

Table 7-10. Model Results for Eastern Site, RELMAP 50th Percentile (utilities only)

Facility	Distance	Air concentration (ng/m3)	%RELMAP	%ISC3	Deposition (µg/m2/yr)	%RELMAP	%ISC3	Soil concentration (ng/g)	%RELMAP	%ISC3	Tier 4 fish concentration (ug/g)	%RELMAP	%ISC3
Large coal-fired utility boiler	2.5 km	0.026	93%	7%	17.9	13%	87%	31	13%	87%	0.43	10%	90%
	10 km	0.026	91%	9%	5.27	44%	56%	9.1	44%	56%	0.11	42%	58%
	25 km	0.026	92%	8%	3.4	69%	31%	5.8	69%	31%	0.064	68%	32%
Medium coal-fired utility boiler	2.5 km	0.027	89%	11%	9.12	26%	74%	16	26%	74%	0.21	21%	79%
	10 km	0.028	88%	12%	4.17	56%	44%	7.2	56%	44%	0.081	54%	46%
	25 km	0.027	90%	10%	3.19	73%	27%	5.5	73%	27%	0.06	73%	27%
Small coal-fired utility boiler	2.5 km	0.028	87%	13%	3.94	59%	41%	6.8	59%	41%	0.08	55%	45%
	10 km	0.027	91%	9%	2.93	80%	20%	5	80%	20%	0.056	78%	22%
	25 km	0.025	96%	4%	2.54	92%	8%	4.4	92%	8%	0.048	92%	8%
Medium oil-fired utility boiler	2.5 km	0.024	99%	1%	2.53	93%	7%	4.3	93%	7%	0.048	91%	9%
	10 km	0.024	99%	1%	2.41	97%	3%	4.1	97%	3%	0.045	97%	3%
	25 km	0.024	99%	1%	2.37	99%	1%	4.1	99%	1%	0.044	99%	1%

Table 7-11. Model Results for Western Site, RELMAP 50th Percentile (utilities only)

Facility	Distance	Air concentration (ng/m3)	%RELMAP	%ISC3	Deposition (ug/m2/yr)	%RELMAP	%ISC3	Soil concentration (ng/g)	%RelMap	%ISC3	Tier 4 fish concentration (ug/g)	%RELMAP	%ISC3
Large coal-fired utility boiler	2.5 km	0.0061	87%	13%	3.9	10%	90%	6.4	10%	90%	0.12	8%	92%
	10 km	0.0066	80%	20%	1.51	25%	75%	2.5	25%	75%	0.04	22%	78%
	25 km	0.0073	73%	27%	1.4	27%	73%	2.3	27%	73%	0.035	25%	75%
Medium coal-fired utility boiler	2.5 km	0.007	76%	24%	2.41	16%	84%	3.9	16%	84%	0.066	14%	86%
	10 km	0.0081	65%	35%	1.75	22%	78%	2.9	22%	78%	0.047	19%	81%
	25 km	0.0076	69%	31%	1.26	30%	70%	2.1	30%	70%	0.032	28%	72%
Small coal-fired utility boiler	2.5 km	0.0077	69%	31%	1.44	26%	74%	2.4	26%	74%	0.04	22%	78%
	10 km	0.0067	79%	21%	0.836	45%	55%	1.4	45%	55%	0.023	39%	61%
	25 km	0.006	89%	11%	0.535	71%	29%	0.88	71%	29%	0.013	68%	32%
Medium oil-fired utility boiler	2.5 km	0.0054	97%	3%	0.471	80%	20%	0.77	80%	20%	0.011	79%	21%
	10 km	0.0054	97%	3%	0.439	86%	14%	0.72	86%	14%	0.011	83%	17%
	25 km	0.0054	98%	2%	0.405	93%	7%	0.66	93%	7%	0.0097	93%	7%

Table 7-12. Predicted Exposure Results for Eastern Site, RELMAP 50th Percentile (utilities only)

Facility	Distance	MHg Exposure (mg/kg/day) Subsistence Fisher	Child of Subsistence Fisher	Recreational Angler	Average recreational angler	%RELMAP	%ISC3
Large coal-fired utility boiler	2.5 km	3.7E-04	5.1E-04	1.8E-04	4.9E-05	10%	90%
	10 km	9.0E-05	1.2E-04	4.5E-05	1.2E-05	42%	58%
	25 km	5.5E-05	7.6E-05	2.8E-05	7.4E-06	68%	32%
Medium coal-fired utility boiler	2.5 km	1.8E-04	2.4E-04	8.9E-05	2.4E-05	21%	79%
	10 km	7.0E-05	9.6E-05	3.5E-05	9.3E-06	54%	46%
	25 km	5.2E-05	7.1E-05	2.6E-05	6.9E-06	73%	27%
Small coal-fired utility boiler	2.5 km	6.9E-05	9.4E-05	3.4E-05	9.2E-06	55%	45%
	10 km	4.8E-05	6.6E-05	2.4E-05	6.4E-06	78%	22%
	25 km	4.1E-05	5.6E-05	2.0E-05	5.5E-06	92%	8%
Medium oil-fired utility boiler	2.5 km	4.1E-05	5.7E-05	2.1E-05	5.5E-06	91%	9%
	10 km	3.9E-05	5.3E-05	1.9E-05	5.2E-06	97%	3%
	25 km	3.8E-05	5.2E-05	1.9E-05	5.1E-06	99%	1%

Table 7-13. Predicted Exposure Results for Western Site, RELMAP 50th Percentile (utilities only)

Facility	Distance	MHg Exposure (mg/kg/day) Subsistence fisher	Child of subsistence fisher	Recreational angler	Average recreational angler	%RELMAP	%ISC3
Large coal-fired utility boiler	2.5 km	1.0E-04	1.4E-04	5.1E-05	1.4E-05	8%	92%
	10 km	3.5E-05	4.8E-05	1.7E-05	4.6E-06	22%	78%
	25 km	3.0E-05	4.2E-05	1.5E-05	4.0E-06	25%	75%
Medium coal-fired utility boiler	2.5 km	5.7E-05	7.8E-05	2.8E-05	7.6E-06	14%	86%
	10 km	4.0E-05	5.5E-05	2.0E-05	5.4E-06	19%	81%
	25 km	2.8E-05	3.8E-05	1.4E-05	3.7E-06	28%	72%
Small coal-fired utility boiler	2.5 km	3.5E-05	4.7E-05	1.7E-05	4.6E-06	22%	78%
	10 km	2.0E-05	2.7E-05	9.9E-06	2.6E-06	39%	61%
	25 km	1.1E-05	1.6E-05	5.7E-06	1.5E-06	68%	32%
Medium oil-fired utility boiler	2.5 km	9.7E-06	1.3E-05	4.9E-06	1.3E-06	79%	21%
	10 km	9.3E-06	1.3E-05	4.6E-06	1.2E-06	83%	17%
	25 km	8.3E-06	1.1E-05	4.2E-06	1.1E-06	93%	7%

concentrations at 25 km from all four sources considered. In the western site at 25 km the local coal combustion source emissions still dominate at 25 km except for the SCUB. The deposition rates at both sites are dominated by the regional sources when compared to the medium oil-fired utility model plant.

The contribution of the local source is identical for the deposition and soil concentrations, but this is not true for the fish concentration. This is because the surface water receives input of mercury from both direct deposition and from erosion/runoff from the watershed. The water body is assumed to lie at the end of the watershed closest to the facility, and so the contribution of the local source to the deposition rate to the water body is generally larger than that for the watershed. This results in a slightly higher contribution of the local source to the predicted fish concentrations.

The multipathway exposure modeling analysis presented in this chapter contains substantial uncertainties and is based on model plants and hypothetical scenarios. Therefore, the results do not apply to any existing utility plant. The analysis and results are useful for gaining a better qualitative understanding of the potential environmental fate of mercury emissions from a model utility plant. However, the quantitative results are uncertain. Further research and analyses are needed to gain a more complete understanding of the mercury exposures due to utility emissions.

Based on the model plant, multipathway exposure modeling analysis of hypothetical scenarios, the daily average methylmercury exposure of the average hypothetical recreational angler (8 g fish consumed per day) is not predicted to exceed the RfD of 1×10^{-4} mg/kg/day under any combination of source, site, and distance. The daily average methylmercury exposure of the high-end hypothetical recreational angler (30 g fish consumed per day) is predicted to exceed the RfD in the eastern site at 2.5 km from the large coal-fired utility boiler (LCUB). The daily average methylmercury exposure of the hypothetical subsistence angler (60 g fish consumed per day) is predicted to exceed the RfD in the eastern site at 2.5 km from the LCUB and at 2.5 km from the MCUB. The daily average methylmercury exposure of the hypothetical subsistence angler is predicted to exceed the RfD in the western site at 2.5 km from the LCUB. Fish consumption by children is predicted to exceed the RfD for several hypothetical general cases: at 2.5 km from the LCUB at either site and at 2.5 km from the MCUB at the eastern site. Background exposures were not considered in this analysis. If background exposures due to other anthropogenic and natural sources were considered, this would obviously result in higher predicted exposures. Total exposures and background exposures are discussed and analyzed in the 1997 EPA *Mercury Study Report to Congress*.[24,26,69]

7.7 CONCLUSIONS

Long-Range Transport Analysis

Based on modeling analysis of the wet and dry deposition of utility air emissions of all forms of mercury within the continental United States, the Agency finds that the following geographic areas have the highest annual rate of total deposition of mercury in all forms (above the 90th percentile level):

- Southeastern Great Lakes and Ohio River Valley
- Most of central and western Pennsylvania
- The urban corridor from Washington, DC, to New York City.
- In the vicinity of many of the larger cities in the eastern United States and in numerous isolated locations where relatively large coal-fired utilities are located.

Areas Predicted to be Least Impacted by Atmospheric Deposition of Mercury from Utilities

Based on modeling analysis of the wet and dry deposition of utility emissions of all forms of mercury within the continental United States, the Agency predicts that the following geographic areas have the lowest annual rate of total deposition of mercury in all forms (below the 10th percentile level):

- Most of the Pacific Coast and Great Basin regions
- Parts of the northern Rocky Mountain region.

The three principal factors that contribute to these modeled deposition patterns are:

- the emission source locations,
- the amount of divalent and particulate mercury emitted or formed in the atmosphere, and
- climate and meteorology.

A facility located in a humid climate is predicted to have a higher annual rate of mercury deposition than a facility located in an arid climate. The critical variables within the model are:

- the estimated washout ratios of elemental and divalent mercury, and
- the annual amount of precipitation.

Precipitation is important because it removes various forms of mercury from the atmosphere and deposits them to the surface of the earth.

The chemical form of emitted mercury is a critical factor in its fate, transport, and toxicity in the environment. The form distributions, or speciation factors, define the estimated fraction of mercury emitted as elemental mercury (Hg0), divalent mercury (Hg^{2+}), or mercury associated with particulates (Hgp). A wide variety of alternate speciation scenarios have been investigated to measure the sensitivity of the RELMAP results to this uncertainty.[74,75] The results show that the total simulated wet and dry deposition of mercury to the continental United States is strongly and positively correlated to the fraction of mercury emitted as Hg^{2+} and Hgp for all major source types.

The differences between the results for the eastern and western sites are due primarily to the differences in the frequency and intensity of precipitation. At the eastern site, precipitation occurs about 12 percent of the year, with about 5 percent of this precipitation of moderate intensity (0.11 to 0.30 inches per hour). By comparison, at the western site, precipitation occurs about 3 percent of the year, with about 2 percent of the precipitation of moderate intensity.

Assessment of Watershed Fate

The atmospheric mercury concentrations and deposition rates estimated using the RELMAP and ISC3 were then used as inputs in the watershed model, IEM-2M, to derive calculations of mercury in watershed soils and surface waters. The soil and water concentrations, in turn, drive calculations of concentrations in the associated biota and fish, which humans are assumed to consume.

IEM-2M Model Sensitivity

For a specific atmospheric deposition rate, mercury concentrations in watersheds and water bodies can vary significantly. Several intrinsic and extrinsic watershed and water body characteristics influence the mercury concentrations in soil, water, and fish. These should cause significant variability in mercury concentrations between regions and among individual lakes within a region.

Mercury concentrations in watershed soils are strongly influenced by atmospheric loading and soil loss processes. The influence of plant canopy and roots in mediating both the loading to the soil and the loss from the soil is not well characterized at present, although published studies indicate its potential importance. Reduction of Hg(II) in the upper soil layer appears to control the volatile loss of mercury, and variations in this reaction can cause significant variations in soil mercury levels. The factors controlling mercury reduction are not well characterized at present. Soil erosion from a watershed can vary more than 3 orders of magnitude depending on

rainfall patterns, soil type, topography, and plant cover. High levels of soil erosion should significantly diminish soil mercury concentrations. Runoff and leaching are not expected to affect soil mercury concentrations significantly.

Total mercury concentrations in a water body are strongly influenced by atmospheric loading and, for drainage lakes, by watershed loading. Variations in watershed size and erosion rates can cause significant variability in lake mercury levels. Hydraulic residence time, the water body volume divided by total flow, affects the maximum possible level of total water column mercury for a given loading rate. Parameters controlling mercury loss through volatilization and net settling can also cause significant variations among lakes. Mercury loss through settling is affected by *in-situ* productivity, by the supply of solids from the watershed, and by the solids-water partition coefficient. DOC concentrations can significantly affect partitioning, and thus overall mercury levels. Mercury loss through volatilization is controlled by the reduction rate, which is a function of sunlight and water clarity. Reduction may also be controlled by pH, with lower values inhibiting this reaction and leading to higher total mercury levels.

Fish mercury levels are strongly influenced by the same factors that control total mercury levels. In addition, fish concentrations are sensitive to methylation and demethylation in the water column and sediments. A set of water body characteristics appear to affect these reactions, including DOC, sediment TOC, sunlight, and water clarity. Variations in these properties can cause significant variations in fish concentrations among lakes. Other factors not examined here, such as anoxia and sulfate concentrations, can stimulate methylation and lead to elevated fish concentrations. Fish mercury levels are sensitive to factors that promote methylmercury mobility from the sediments to the water column; these factors include sediment DOC and sediment-pore water partition coefficients.

Limitations of the Local Scale and Watershed Analyses

There are limitations associated with the fate and transport analyses. These have to do to a large degree with the current state-of-the-science concerning mercury fate and transport in the terrestrial and aquatic environments and variability between waterbodies. A few important limitations were discussed previously. Additional important limitations are discussed below.

- There is a lack of information characterizing the movement of mercury from watershed soils to water bodies and the rates at which mercury converts from one chemical species to another. There appears to be a great deal of variability in these factors among watersheds.

- There are not conclusive data on the amount of and rates of mercury methylation in different types of water bodies. In addition, there is a lack of data on the transfer of mercury between environmental compartments and biologic compartments; for example, the link between the amount of mercury in the water body and the levels in fish appears to vary from water body to water body.

Conclusions Regarding Mercury Fate and Transport in the Environment

The uncertainty inherent in the modeled estimates in this study arises from many individual assumptions present within the three models. Because of these uncertainties, EPA interpreted the model results qualitatively rather than quantitatively as follows.

The analyses conducted for this study as well as for the EPA's Mercury Study and available scientific knowledge indicate that human activities today are adding to the mercury reservoirs that already exist in land, water, and air, both naturally and as a result of previous human activities.

The analysis of mercury fate and transport conducted for this study, in conjunction with available scientific knowledge, supports a plausible link between mercury emissions from utility combustion sources and mercury concentrations in air, soil, water, and sediments. The critical variables contributing to this linkage are:

- the species of mercury that are emitted from the sources, with Hg0 mostly contributing to concentrations in ambient air and Hg^{2+} mostly contributing to concentrations in soil, water and sediments;

- the overall amount of mercury emitted from a combustion source;

- the watershed soil loss rates, including reduction and erosion;

- the water body loss rates, including outflow, reduction, and settling; and

- the climate conditions.

In addition, this study also supports a plausible link between mercury emissions from utility combustion sources and methylmercury concentrations in freshwater fish. The critical variables contributing to this linkage are:

- the species of mercury that are emitted, with emitted divalent mercury mostly depositing into local watershed areas and, to a lesser extent the atmospheric conversion of

elemental mercury to divalent species which are deposited over greater distances;

- the overall amount of mercury emitted from a source;
- the watershed soil loss rates, including reduction and erosion;
- the water body loss rates, including outflow, reduction, and settling;
- the extent of mercury methylation in the water body;
- the extent of food web bioaccumulation in the water body; and
- the climate conditions.

From the analysis of deposition and on a comparative basis, the deposition of Hg^{2+} close to an emission source is greater for receptors in elevated terrain (i.e., terrain above the elevation of the stack base) than from receptors located in flat terrain (i.e., terrain below the elevation of the stack base). The critical variables are parameters that influence the plume height, primarily the stack height and stack exit gas velocity.

On a national scale, an apportionment between sources of mercury and mercury in environmental media and biota cannot be described in quantitative terms with the current scientific understanding of the environmental fate and transport of this pollutant.

Human Exposure

The only exposure route considered was the consumption of freshwater fish. Consumption of fish is the dominant pathway of exposure to methylmercury for fish-consuming humans. There is a great deal of variability among individuals in these populations with respect to fish consumption rates. As a result, there is a great deal of variability in exposure to methylmercury in these populations. While EPA interprets these models qualitatively, some freshwater fish-consuming individuals are predicted to exceed the RfD as a result of mercury emissions from the sources considered. Measuring methylmercury concentrations in fish from these waters and more direct measures of exposure (e.g., hair or blood data) to humans consuming fish around these sources should be a research priority.

It is important to note that the utility contribution is only one component of the total amount of methylmercury in fish. Other anthropogenic sources, natural sources and the existing background are expected to influence fish methylmercury levels.

7.8 DISCUSSION OF POTENTIAL CONCERNS OF MERCURY EMISSIONS FROM UTILITIES

Mercury is considered the highest priority for multipathway analyses because it is an environmentally persistent, toxic element. Mercury is deposited to soil and terrestrial vegetation through terrestrial exposure pathways, but at levels that do not result in human exposures likely to be detrimental to health. However, in its methylated form mercury bioaccumulates in the food web (especially the aquatic food web). Modeling results suggest that most of the mercury emitted to the atmosphere is deposited more than 50 km away from the source, especially sources that have tall stacks. As stated above, the modeling assessment from the Mercury Study, in conjunction with available scientific knowledge, supports a plausible link between anthropogenic mercury emissions and mercury found in freshwater fish. Additional emissions to air will contribute to levels in the global reservoir and deposition to water bodies. As a result, mercury emissions from utility units may add to the existing environmental burden.

At this time, the available information, on balance, indicates that utility mercury emissions are of sufficient potential concern for public health to merit further research and monitoring. The EPA recognizes that there are substantial uncertainties that make it difficult to quantify the magnitude of the risks due to utility mercury emissions, and that further research and/or evaluation would be needed to reduce these uncertainties. Remaining questions include the following: (1) what is the quantitative relationship between a change in United States mercury emissions and the resulting change in methylmercury levels in fish; (2) what are the actual consumption patterns and estimated methylmercury exposures of the subpopulations of concern; (3) what are the actual mercury levels in a statistically valid and representative sample of the U.S. population and susceptible subpopulations; (4) what exposure levels are likely to result in adverse health effects; (5) what affects the formation of methylmercury in waterbodies and its bioaccumulation in fish; (6) how much mercury is emitted from natural sources and past anthropogenic sources; and (7) how much mercury is removed during coal cleaning and other ongoing practices for pollution control. New data that could reduce some of the uncertainties are likely to become available in the next several years, and EPA plans to review and consider these data, as appropriate, in future decisions.

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IN THE UNITED STATES DISTRICT COURT
FOR THE SOUTHERN DISTRICT OF ILLINOIS

UNITED STATES OF AMERICA Plaintiff, and THE STATE OF ILLINOIS, AMERICAN BOTTOM CONSERVANCY, HEALTH AND ENVIRONMENTAL JUSTICE – ST. LOUIS, INC., ILLINOIS STEWARDSHIP ALLIANCE, and PRAIRIE RIVERS NETWORK Plaintiff - Intervenors, v. ILLINOIS POWER COMPANY and DYNEGY MIDWEST GENERATION, INC., Defendants.	)	Civil Action No. 99-833-MJR

CONSENT DECREE

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Appendix A: Environmental Mitigation Projects

WHEREAS, the United States of America ("the United States"), on behalf of the United States Environmental Protection Agency ("EPA") filed a Complaint against Illinois Power Company ("Illinois Power") on November 3, 1999, and Amended Complaints against Illinois Power Company and Dynegy Midwest Generation, Inc. ("DMG") on January 19, 2000, March 14, 2001, and March 7, 2003, pursuant to Sections 113(b) and 167 of the Clean Air Act (the "Act"), 42 U.S.C. §§ 7413(b) and 7477, for injunctive relief and the assessment of civil penalties for alleged violations at the Baldwin Generating Station of:

(a) the Prevention of Significant Deterioration provisions in Part C of Subchapter I of the Act, 42 U.S.C. §§ 7470-92;

(b) the federally enforceable State Implementation Plan developed by the State of Illinois (the "Illinois SIP"); and

(c) the New Source Performance Standard provisions in Part A of Subchapter I of the Act, 42 U.S.C. § 7411.

WHEREAS, EPA issued Notices of Violation with respect to such allegations to Illinois Power on November 3, 1999 and November 26, 2000;

WHEREAS, EPA provided Illinois Power, DMG, and the State of Illinois actual notice of violations pertaining to its alleged violations, in accordance with Section 113(a)(1) and (b) of the Act, 42 U.S.C. § 7413(a)(1) and (b);

WHEREAS, Illinois Power was the owner and operator of the Baldwin Facility from 1970 to October 1999. On October 1, 1999, Illinois Power transferred the Baldwin Facility to Illinova Corporation. Illinova Corporation then contributed the Baldwin Facility to Illinova

Power Marketing, Inc., after which time Illinois Power no longer owned or operated the Baldwin Facility.

WHEREAS, beginning on October 1, 1999 and continuing through the date of lodging of this Consent Decree, Illinois Power has been neither the owner nor the operator of the Baldwin Facility or of any of the Units in the DMG System which are affected by this Consent Decree;

WHEREAS, in February 2000, Illinova Corporation merged with Dynegy Holdings Inc. and became a wholly owned subsidiary of Dynegy Inc. (referred to herein as "Dynegy"). Thereafter, Illinova Power Marketing, Inc., the owner of the Baldwin Facility, changed its name to Dynegy Midwest Generation, Inc. (referred to herein as "DMG"). On September 30, 2004, Dynegy, through Illinova, sold Illinois Power to Ameren Corporation.

WHEREAS, Ameren and Illinova Corporation, a subsidiary of Dynegy, have entered into an agreement which provides for the escrow of certain funds, the release of which funds is related to the resolution of certain contingent environmental liabilities that were alleged in the above-referenced Amended Complaints against Illinois Power and DMG.

WHEREAS, Plaintiff-Intervenors – the American Bottom Conservancy, Health and Environmental Justice - St. Louis, Inc., Illinois Stewardship Alliance, the Prairie Rivers Network, and the State of Illinois – moved to intervene on September 25, 2003 and filed Complaints in Intervention. The Court granted intervention to all movants on October 23, 2003.

WHEREAS, in their Complaints, Plaintiff United States and Plaintiff Intervenors (collectively "Plaintiffs") allege, *inter alia*, that Illinois Power and DMG failed to obtain the necessary permits and install the controls necessary under the Act to reduce sulfur dioxide,

nitrogen oxides, and/or particulate matter emissions, and that such emissions can damage human health and the environment;

WHEREAS, the Plaintiffs' Complaints state claims upon which relief can be granted against Illinois Power and DMG under Sections 113 and 167 of the Act, 42 U.S.C. §§ 7413 and 7477, and 28 U.S.C. § 1355;

WHEREAS, DMG and Illinois Power have denied and continue to deny the violations alleged in the Complaints, maintain that they have been and remain in compliance with the Act and are not liable for civil penalties or injunctive relief, and DMG is agreeing to the obligations imposed by this Consent Decree solely to avoid further costs and uncertainty;

WHEREAS, DMG has installed equipment for the control of nitrogen oxides emissions at the Baldwin Facility, including Overfire Air systems on Baldwin Units 1, 2, and 3, Low NO_X Burners on Baldwin Unit 3 and Selective Catalytic Reduction ("SCR") Systems on Baldwin Units 1 and 2, resulting in a reduction in emissions of nitrogen oxides from the Baldwin Plant of approximately 65% below 1999 levels from 55,026 tons in 1999 to 19,061 tons in 2003;

WHEREAS, DMG switched from use of high sulfur coal to low sulfur Powder River Basin coal at Baldwin Units 1, 2 and 3 in 1999 and 2000, resulting in a reduction in emissions of sulfur dioxide from the Baldwin Plant of approximately 90% below 1999 levels from 245,243 tons in 1999 to 26,311 tons in 2003;

WHEREAS, the Parties anticipate that the installation and operation of pollution control equipment pursuant to this Consent Decree will achieve significant additional reductions of SO_2, NO_x, and PM emissions and thereby further improve air quality;

WHEREAS, in June of 2003, the liability stage of the litigation resulting from the United States' claims was tried to the Court and no decision has yet been rendered; and

WHEREAS, the Plaintiffs, DMG and Illinois Power have agreed, and the Court by entering this Consent Decree finds: that this Consent Decree has been negotiated in good faith and at arms length; that this settlement is fair, reasonable, in the best interest of the Parties and in the public interest, and consistent with the goals of the Act; and that entry of this Consent Decree without further litigation is the most appropriate means of resolving this matter;

NOW, THEREFORE, without any admission by the Defendants, and without adjudication of the violations alleged in the Complaints or the NOVs, it is hereby ORDERED, ADJUDGED, AND DECREED as follows:

I. JURISDICTION AND VENUE

1. This Court has jurisdiction over this action, the subject matter herein, and the Parties consenting hereto, pursuant to 28 U.S.C. §§ 1331, 1345, 1355, and 1367, Sections 113 and 167 of the Act, 42 U.S.C. §§ 7413 and 7477, and Section 42(e) of the Illinois Environmental Protection Act, 415 ILCS 5/42(e). Venue is proper under Section 113(b) of the Act, 42 U.S.C. § 7413(b), and under 28 U.S.C. § 1391(b) and (c). Solely for the purposes of this Consent Decree and the underlying Complaints, and for no other purpose, Defendants waive all objections and defenses that they may have to the Court's jurisdiction over this action, to the Court's jurisdiction over the Defendants, and to venue in this District. Defendants shall not challenge the terms of this Consent Decree or this Court's jurisdiction to enter and enforce this Consent Decree. Solely for purposes of the Complaints filed by the Plaintiffs in this matter and resolved by the Consent Decree, for purposes of entry and enforcement of this Consent Decree,

and for no other purpose, Defendants waive any defense or objection based on standing. Except as expressly provided for herein, this Consent Decree shall not create any rights in or obligations of any party other than the Plaintiffs and the Defendants. Except as provided in Section XXVI (Public Comment) of this Consent Decree, the Parties consent to entry of this Consent Decree without further notice.

II. APPLICABILITY

2. Upon entry, the provisions of the Consent Decree shall apply to and be binding upon and inure to the benefit of the Citizen Plaintiffs and DMG, and their respective successors and assigns, officers, employees and agents, solely in their capacities as such, and the State of Illinois and the United States. Illinois Power is a Party to this Consent Decree, is the beneficiary of Section X of this Consent Decree (Release and Covenant Not to Sue for Illinois Power Company), and is subject to Paragraph 171 and the other applicable provisions of the Consent Decree as specified in such Paragraph in the event it acquires an Ownership Interest in, or becomes an operator (as that term is used and interpreted under the Clean Air Act) of, any DMG System Unit, but otherwise has no other obligations under this Consent Decree except as expressly specified herein.

3. DMG shall be responsible for providing a copy of this Consent Decree to all vendors, suppliers, consultants, contractors, agents, and any other company or other organization retained to perform any of the work required by this Consent Decree. Notwithstanding any retention of contractors, subcontractors, or agents to perform any work required under this Consent Decree, DMG shall be responsible for ensuring that all work is performed in accordance with the requirements of this Consent Decree. In any action to enforce this Consent Decree,

DMG shall not assert as a defense the failure of its officers, directors, employees, servants, agents, or contractors to take actions necessary to comply with this Consent Decree, unless DMG establishes that such failure resulted from a Force Majeure Event, as defined in Paragraph 137 of this Consent Decree.

III. DEFINITIONS

4. A "30-Day Rolling Average Emission Rate" for a Unit shall be expressed as lb/mmBTU and calculated in accordance with the following procedure: first, sum the total pounds of the pollutant in question emitted from the Unit during an Operating Day and the previous twenty-nine (29) Operating Days; second, sum the total heat input to the Unit in mmBTU during the Operating Day and the previous twenty-nine (29) Operating Days; and third, divide the total number of pounds of the pollutant emitted during the thirty (30) Operating Days by the total heat input during the thirty (30) Operating Days. A new 30-Day Rolling Average Emission Rate shall be calculated for each new Operating Day. Each 30-Day Rolling Average Emission Rate shall include all emissions that occur during all periods of startup, shutdown and Malfunction within an Operating Day, except as follows:

a. Emissions and BTU inputs that occur during a period of Malfunction shall be excluded from the calculation of the 30-Day Rolling Average Emission Rate if DMG provides notice of the Malfunction to EPA and the State in accordance with Paragraph 138 in Section XV (Force Majeure) of this Consent Decree;

b. Emissions of NO_x and BTU inputs that occur during the fifth and subsequent Cold Start Up Period(s) that occur at a given Unit during any 30-day period shall be excluded from the calculation of the 30-Day Rolling Average Emission Rate if

inclusion of such emissions would result in a violation of any applicable 30-Day Rolling Average Emission Rate and DMG has installed, operated and maintained the SCR in question in accordance with manufacturers' specifications and good engineering practices. A "Cold Start Up Period" occurs whenever there has been no fire in the boiler of a Unit (no combustion of any Fossil Fuel) for a period of six (6) hours or more. The NO_x emissions to be excluded during the fifth and subsequent Cold Start Up Period(s) shall be the lesser of (i) those NO_x emissions emitted during the eight (8) hour period commencing when the Unit is synchronized with a utility electric transmission system and concluding eight (8) hours later, or (ii) those NO_x emissions emitted prior to the time that the flue gas has achieved the minimum SCR operational temperature specified by the catalyst manufacturer; and

c. For a Unit that has ceased firing Fossil Fuel, emissions of SO_2 and Btu inputs that occur during any period, not to exceed two (2) hours, from the restart of the Unit to the time the Unit is fired with any coal, shall be excluded from the calculation of the 30-Day Rolling Average Emission Rate.

5. "Baghouse" means a fullstream (fabric filter) particulate emission control device.

6. "Boiler Island" means a Unit's (A) fuel combustion system (including bunker, coal pulverizers, crusher, stoker, and fuel burners); (B) combustion air system; (C) steam generating system (firebox, boiler tubes, and walls); and (D) draft system (excluding the stack), all as further described in "Interpretation of Reconstruction," by John B. Rasnic U.S. EPA (November 25, 1986) and attachments thereto.

7. "Capital Expenditure" means all capital expenditures, as defined by Generally Accepted Accounting Principles ("GAAP"), as those principles exist at the date of entry of this Consent Decree, excluding the cost of installing or upgrading pollution control devices.

8. "CEMS" or "Continuous Emission Monitoring System" means, for obligations involving NO_x and SO_2 under this Consent Decree, the devices defined in 40 C.F.R. § 72.2 and installed and maintained as required by 40 C.F.R. Part 75.

9. "Citizen Plaintiffs" means, collectively, the American Bottom Conservancy, Health and Environmental Justice - St. Louis, Inc., Illinois Stewardship Alliance, and the Prairie Rivers Network.

10. "Clean Air Act" or "Act" means the federal Clean Air Act, 42 U.S.C. §§7401-7671q, and its implementing regulations.

11. "Consent Decree" or "Decree" means this Consent Decree and the Appendix hereto, which is incorporated into this Consent Decree.

12. "Defendants" means Dynegy Midwest Generation, Inc. and Illinois Power Company.

13. "DMG" means Dynegy Midwest Generation, Inc.

14. "DMG System" means, solely for purposes of this Consent Decree, the following ten (10) listed coal-fired, electric steam generating Units (with the rated gross MW capacity of each Unit, reported to Mid-America Interconnected Network ("MAIN") in 2003, noted in parentheses), located at the following plants:

- Baldwin Generating Station in Baldwin, Illinois: Unit 1 (624 MW), 2 (629 MW), 3 (629 MW);

- Havana Generating Station in Havana, Illinois: Unit 6 (487 MW);
- Hennepin Generating Station in Hennepin, Illinois: Unit 1 (81 MW), Unit 2 (240 MW);
- Vermilion Generating Station in Oakwood, Illinois: Unit1 (84 MW), Unit 2 (113 MW);
- Wood River Generating Station in Alton, Illinois: Unit 4 (105 MW), Unit 5 (383 MW).

15. "Emission Rate" means the number of pounds of pollutant emitted per million BTU of heat input ("lb/mmBTU"), measured in accordance with this Consent Decree.

16. "EPA" means the United States Environmental Protection Agency.

17. "ESP" means electrostatic precipitator, a pollution control device for the reduction of PM.

18. "Existing Units" means those Units included in the DMG System.

19. "Flue Gas Desulfurization System," or "FGD," means a pollution control device with one or more absorber vessels that employs flue gas desulfurization technology for the reduction of sulfur dioxide.

20. "Fossil Fuel" means any hydrocarbon fuel, including coal, petroleum coke, petroleum oil, or natural gas.

21. "Illinois Environmental Protection Act" means the Illinois Environmental Protection Act, 415 ILCS 5/1 et. seq., and its implementing regulations.

22. "Illinois Power" means the Illinois Power Company.

23. "Improved Unit" means, in the case of NO_x, a DMG System Unit equipped with or scheduled under this Consent Decree to be equipped with an SCR, or, in the case of SO_2, a DMG System Unit scheduled under this Consent Decree to be equipped with an FGD (or equivalent SO_2 control technology approved pursuant to Paragraph 68). A Unit may be an Improved Unit for one pollutant without being an Improved Unit for the other. Any Other Unit can become an Improved Unit if (a) in the case of NO_x, it is equipped with an SCR (or equivalent NOx control technology approved pursuant to Paragraph 64) and has become subject to a federally enforceable 0.100 lb/mmBTU NO_x 30-Day Rolling Average Emission Rate, or (b) in the case of SO_2, it is equipped with an FGD (or equivalent SO_2 control technology approved pursuant to Paragraph 68) and has become subject to a federally enforceable 0.100 lb/mmBTU SO_2 30-Day Rolling Average Emission Rate, and (c) in the case of NO_x or SO_2, the requirement to achieve and maintain a 0.100 lb/mmBTU 30-Day Rolling Average Emission Rate is incorporated into the Title V Permit applicable to that Unit or, if no Title V Permit exists, a modification to this Consent Decree that is agreed to by the Plaintiffs and DMG and approved by this Court.

24. "lb/mmBTU" means one pound per million British thermal units.

25. "Malfunction" means any sudden, infrequent, and not reasonably preventable failure of air pollution control equipment, process equipment, or a process to operate in a normal or usual manner. Failures that are caused in part by poor maintenance or careless operation are not Malfunctions.

26. "MW" means a megawatt or one million Watts.

27. “National Ambient Air Quality Standards” or “NAAQS” means national ambient air quality standards that are promulgated pursuant to Section 109 of the Act, 42 U.S.C. § 7409.

28. “Nonattainment NSR” means the nonattainment area New Source Review program within the meaning of Part D of Subchapter I of the Act, 42 U.S.C. §§ 7501-7515, 40 C.F.R. Part 51.

29. “NO_x” means oxides of nitrogen.

30. “NO_x Allowance” means an authorization or credit to emit a specified amount of NO_x that is allocated or issued under an emissions trading or marketable permit program of any kind that has been established under the Clean Air Act or a State Implementation Plan.

31. “Operating Day” means any calendar day on which a Unit fires Fossil Fuel; provided, however, that exclusively for purposes of Paragraph 36, “Operating Day” means any calendar day on which both Baldwin Unit 1 and Baldwin Unit 2 fire Fossil Fuel.

32. “Other Unit” means any Unit of the DMG System that is not an Improved Unit for the pollutant in question.

33. “Ownership Interest” means part or all of DMG’s legal or equitable ownership interest in any Unit in the DMG System.

34. “Parties” means the United States, the State of Illinois, the Citizen Plaintiffs, DMG, and Illinois Power.

35. “Plaintiffs” means the United States, the State of Illinois, and the Citizen Plaintiffs.

36. A “Plant-Wide 30-Day Rolling Average Emission Rate” shall be expressed as lb/mmBTU and calculated in accordance with the following procedure: first, sum the total

pounds of the pollutant in question emitted from all three Units at the Baldwin Plant during an Operating Day and the previous twenty-nine (29) Operating Days; second, sum the total heat input to all three Units at the Baldwin Plant in mmBTU during the Operating Day and the previous twenty-nine (29) Operating Days; and third, divide the total number of pounds of the pollutant emitted from all three Baldwin Units during the thirty (30) Operating Days by the total heat input to all three Baldwin Units during the thirty (30) Operating Days. A new Plant-Wide 30-Day Rolling Average Emission Rate shall be calculated for each new Operating Day. Each Plant-Wide 30-Day Rolling Average Emission Rate shall include all emissions that occur during all periods of startup, shutdown and Malfunction within an Operating Day. A Malfunction shall be excluded from this Emission Rate, however, if DMG satisfies the Force Majeure provisions of this Consent Decree.

37. A "Plant-Wide Annual Tonnage Emission Level" means, for the purposes of Section XI of this Decree, the number of tons of the pollutant in question that may be emitted from the plant at issue during the relevant calendar year (i.e., January 1 through December 31), and shall include all emissions of the pollutant emitted during periods of startup, shutdown, and Malfunction.

38. "Pollution Control Equipment Upgrade Analysis" means the technical study, analysis, review, and selection of control technology recommendations (including an emission rate or removal efficiency) required to be performed in connection with an application for a federal PSD permit, taking into account the characteristics of the existing facility. Except as otherwise provided in this Consent Decree, such study, analysis, review, and selection of recommendations shall be carried out in accordance with applicable federal and state regulations

and guidance describing the process and analysis for determining Best Available Control Technology (BACT), as that term is defined in 40 C.F.R. §52.21(b)(12), including, without limitation, the December 1, 1987 EPA Memorandum from J. Craig Potter, Assistant Administrator for Air and Radiation, regarding Improving New Source Review (NSR) Implementation. Nothing in this Decree shall be construed either to: (a) alter the force and effect of statements known as or characterized as "guidance" or (b) permit the process or result of a "Pollution Control Equipment Upgrade Analysis" to be considered BACT for any purpose under the Act.

39. "PM Control Device" means any device, including an ESP or a Baghouse, that reduces emissions of particulate matter (PM).

40. "PM" means particulate matter.

41. "PM CEMS" or "PM Continuous Emission Monitoring System" means the equipment that samples, analyzes, measures, and provides, by readings taken at frequent intervals, an electronic or paper record of PM emissions.

42. "PM Emission Rate" means the number of pounds of PM emitted per million BTU of heat input (lb/mmBTU), as measured in annual stack tests in accordance with EPA Method 5, 40 C.F.R. Part 60, including Appendix A.

43. "Project Dollars" means DMG's expenditures and payments incurred or made in carrying out the Environmental Mitigation Projects identified in Section VIII (Environmental Mitigation Projects) of this Consent Decree to the extent that such expenditures or payments both: (a) comply with the requirements set forth in Section VIII (Environmental Mitigation Projects) and Appendix A of this Consent Decree, and (b) constitute DMG's direct payments for

such projects, DMG's external costs for contractors, vendors, and equipment, or DMG's internal costs consisting of employee time, travel, or out-of-pocket expenses specifically attributable to these particular projects and documented in accordance with GAAP.

44. "PSD" means Prevention of Significant Deterioration within the meaning of Part C of Subchapter I of the Clean Air Act, 42 U.S.C. §§ 7470 - 7492 and 40 C.F.R. Part 52.

45. "Selective Catalytic Reduction System" or "SCR" means a pollution control device that employs selective catalytic reduction technology for the reduction of NO_x emissions.

46. "SO_2" means sulfur dioxide.

47. "SO_2 Allowance" means "allowance" as defined at 42 U.S.C. § 7651a(3): "an authorization, allocated to an affected unit by the Administrator of EPA under Subchapter IV of the Act, to emit, during or after a specified calendar year, one ton of sulfur dioxide."

48. "System-Wide Annual Tonnage Limitation" means the limitation on the number of tons of the pollutant in question that may be emitted from the DMG System during the relevant calendar year (i.e., January 1 through December 31), and shall include all emissions of the pollutant emitted during periods of startup, shutdown, and Malfunction.

49. "Title V Permit" means the permit required of DMG's major sources under Subchapter V of the Act, 42 U.S.C. §§ 7661-7661e.

50. "Unit" means collectively, the coal pulverizer, stationary equipment that feeds coal to the boiler, the boiler that produces steam for the steam turbine, the steam turbine, the generator, the equipment necessary to operate the generator, steam turbine and boiler, and all ancillary equipment, including pollution control equipment. An electric steam generating station may comprise one or more Units.

IV. NO_x EMISSION REDUCTIONS AND CONTROLS

A. NO_x Emission Controls

51. Beginning 45 days after entry of this Consent Decree, and continuing thereafter, DMG shall commence operation of the SCRs installed at Baldwin Unit 1, Unit 2, and Havana Unit 6 so as to achieve and maintain a 30-Day Rolling Average Emission Rate from each such Unit of not greater than 0.100 lb/mmBTU NO_x.

52. Beginning 45 days after entry of this Consent Decree, and continuing thereafter, DMG shall achieve and maintain a Plant-Wide 30-Day Rolling Average Emission Rate of not greater than 0.100 lb/mmBTU NO_x at the Baldwin Plant.

53. Beginning 45 days after entry of this Consent Decree, and continuing thereafter, subject to paragraph 54 below, DMG shall achieve and maintain a 30-Day Rolling Average Emission Rate of not greater than 0.120 lb/mmBTU NO_x at Baldwin Unit 3.

54. Beginning on December 31, 2012, and continuing thereafter, DMG shall maintain a 30-Day Rolling Average Emission Rate of not greater than 0.100 lb/mmBTU NO_x at Baldwin Unit 3.

55. Beginning 30 days after entry of this Consent Decree, and continuing thereafter, DMG shall operate each SCR in the DMG System at all times when the Unit it serves is in operation, provided that such operation of the SCR is consistent with the technological limitations, manufacturers' specifications, and good engineering and maintenance practices for the SCR. During any such period in which the SCR is not operational, DMG will minimize emissions to the extent reasonably practicable.

56. Beginning 45 days from entry of this Consent Decree, DMG shall operate low NO_x burners ("LNB") and/or Overfire Air Technology ("OFA") on the DMG System Units listed in the table below at all times that the Units are in operation, consistent with the technological limitations, manufacturers' specifications, and good engineering and maintenance practices for the LNB and/or the Overfire Air Technology, so as to minimize emissions to the extent reasonably practicable.

DMG System Unit	**NOx Control Technology**
Baldwin Unit 1	OFA
Baldwin Unit 2	OFA
Baldwin Unit 3	LNB, OFA
Havana Unit 6	LNB, OFA
Hennepin Unit 1	LNB, OFA
Hennepin Unit 2	LNB, OFA
Vermilion Unit 2	LNB, OFA
Wood River Unit 4	LNB, OFA
Wood River Unit 5	LNB, OFA

B. System-Wide Annual Tonnage Limitations for NO_x

57. During each calendar year specified in the Table below, all Units in the DMG System, collectively, shall not emit NO_x in excess of the following System-Wide Annual Tonnage Limitations:

Applicable Calendar Year	System-Wide Annual Tonnage Limitations for NO_x
2005	15,000 tons
2006	14,000 tons
2007 and each year thereafter	13,800 tons

C. Use of NO_x Allowances

58. Except as provided in this Consent Decree, DMG shall not sell or trade any NO_x Allowances allocated to the DMG System that would otherwise be available for sale or trade as a result of the actions taken by DMG to comply with the requirements of this Consent Decree.

59. Except as may be necessary to comply with Section XIV (Stipulated Penalties), DMG may not use NO_x Allowances to comply with any requirement of this Consent Decree, including by claiming compliance with any emission limitation required by this Decree by using, tendering, or otherwise applying NO_x Allowances to offset any excess emissions (i.e., emissions above the limits specified in Paragraph 57).

60. NO_x Allowances allocated to the DMG System may be used by DMG only to meet its own federal and/or state Clean Air Act regulatory requirements, except as provided in Paragraph 61.

61. Provided that DMG is in compliance with the System-Wide Annual Tonnage Limitations for NO_x set forth in this Consent Decree, nothing in this Consent Decree shall preclude DMG from selling or transferring NO_x Allowances allocated to the DMG System that become available for sale or trade solely as a result of:

a. activities that reduced NO_x emissions at any Unit within the DMG System prior to the date of entry of this Consent Decree;

b. the installation and operation of any NO_x pollution control technology or technique that is not otherwise required by this Consent Decree; or

c. achievement and maintenance of NO_x emission rates below a 30-Day Rolling Average Emission Rate of 0.100 lb/mmBTU at Baldwin Units 1, 2 or 3, or at Havana Unit 6,

so long as DMG timely reports the generation of such surplus NO_x Allowances in accordance with Section XII (Periodic Reporting) of this Consent Decree. DMG shall be allowed to sell or transfer NO_x Allowances equal to the NO_x emissions reductions achieved for any given year by any of the actions specified in Subparagraphs 61.b or 61.c. only to the extent that, and in the amount that, the total NO_x emissions from all Units within the DMG System are below the System-Wide Annual Tonnage Limitation specified in Paragraph 57 for that year.

62. Nothing in this Consent Decree shall prevent DMG from purchasing or otherwise obtaining NO_x Allowances from another source for purposes of complying with state or federal Clean Air Act requirements to the extent otherwise allowed by law.

D. <u>NO_x Provisions - Improving Other Units</u>

63. Any Other Unit can become an Improved Unit for NO_x if (a) it is equipped with an SCR (or equivalent NOx control technology approved pursuant to Paragraph 64), and (b) has become subject to a federally enforceable 0.100 lb/mmBTU NO_x 30-Day Rolling Average Emission Rate.

64. With prior written notice to the Plaintiffs and written approval from EPA (after consultation with the State of Illinois and the Citizen Plaintiffs), an Other Unit in the DMG System may be considered an Improved Unit under this Consent Decree if DMG installs and

operates NO_x control technology, other than an SCR, that has been demonstrated to be capable of achieving and maintaining a 30-Day Rolling Average Emission Rate not greater than 0.100 lb/mmBTU NO_x and if such unit has become subject to a federally enforceable 0.100 lb/mmBTU NO_x 30-Day Rolling Average Emission Rate.

E. General NO_x Provisions

65. In determining Emission Rates for NO_x, DMG shall use CEMS in accordance with the reference methods specified in 40 C.F.R. Part 75.

V. SO_2 EMISSION REDUCTIONS AND CONTROLS

A. SO_2 Emission Limitations and Control Requirements

66. No later than the dates set forth in the Table below for each of the three Units at Baldwin and Havana Unit 6, and continuing thereafter, DMG shall not operate the specified Unit unless and until it has installed and commenced operation of, on a year-round basis, an FGD (or equivalent SO_2 control technology approved pursuant to Paragraph 68) on each such Unit, so as to achieve and maintain a 30-Day Rolling Average Emission Rate of not greater than 0.100 lb/mmBTU SO_2.

UNIT	**DATE**
First Baldwin Unit (i.e., any of the Baldwin Units 1, 2 or 3)	December 31, 2010
Second Baldwin Unit (i.e., either of the 2 remaining Baldwin Units)	December 31, 2011
Third Baldwin Unit (i.e., the remaining Baldwin Unit)	December 31, 2012
Havana Unit 6	December 31, 2012

67. Any FGD required to be installed under this Consent Decree may be a wet FGD or a dry FGD at DMG's option.

68. With prior written notice to the Plaintiffs and written approval from EPA (after consultation by EPA with the State of Illinois and the Citizen Plaintiffs), DMG may, in lieu of installing and operating an FGD at any of the Units specified in Paragraph 66, install and operate equivalent SO_2 control technology so long as such equivalent SO_2 control technology has been demonstrated to be capable of achieving and maintaining a 30-Day Rolling Average Emission Rate of not greater than 0.100 lb/mmBTU SO_2.

69. Beginning on the later of the date specified in Paragraph 66 or the first Operating Day of each Unit thereafter, and continuing thereafter, DMG shall operate each FGD (or equivalent SO_2 control technology approved pursuant to Paragraph 68) required by this Consent Decree at all times that the Unit it serves is in operation, provided that such operation of the FGD or equivalent technology is consistent with the technological limitations, manufacturers' specifications, and good engineering and maintenance practices for the FGD or equivalent technology. During any such period in which the FGD or equivalent technology is not operational, DMG will minimize emissions to the extent reasonably practicable.

70. No later than 30 Operating Days after entry of this Consent Decree, and continuing thereafter, DMG shall operate Hennepin Units 1 and 2 and Wood River Units 4 and 5 so as to achieve and maintain a 30-Day Rolling Average Emission Rate from each of the stacks serving such Units of not greater than 1.200 lb/mmBtu SO_2.

71. DMG shall operate Vermilion Units 1 and 2 so that no later than 30 Operating Days after January 1, 2007, DMG shall achieve and maintain a 30-Day Rolling Average Emission Rate from the stack serving such Units of not greater than 1.200 lb/mmBtu SO_2.

72. No later than 30 Operating Days after entry of this Consent Decree and continuing until December 31, 2012, DMG shall operate Havana Unit 6 so as to achieve and maintain a 30-Day Rolling Average Emission Rate from the stack serving such Unit of not greater than 1.200 lb/mmBtu SO_2 .

B. System-Wide Annual Tonnage Limitations for SO_2

73. During each calendar year specified in the Table below, all Units in the DMG System, collectively, shall not emit SO_2 in excess of the following System-Wide Annual Tonnage Limitations:

Applicable Calendar Year	**System-Wide Annual Tonnage Limitations for SO_2**
2005	66,300 tons
2006	66,300 tons
2007	65,000 tons
2008	62,000 tons
2009	62,000 tons
2010	62,000 tons
2011	57,000 tons
2012	49,500 tons
2013 and each year thereafter	29,000 tons

74. Except as may be necessary to comply with Section XIV (Stipulated Penalties), DMG may not use SO_2 Allowances to comply with any requirement of this Consent Decree,

including by claiming compliance with any emission limitation required by this Decree by using, tendering, or otherwise applying SO_2 Allowances to offset any excess emissions (i.e., emissions above the limits specified in Paragraph 73).

C. Surrender of SO_2 Allowances

75. For each year specified below, DMG shall surrender to EPA, or transfer to a non-profit third party selected by DMG for surrender, SO_2 Allowances that have been allocated to DMG for the specified calendar year by the Administrator of EPA under the Act or by any State under its State Implementation Plan, in the amounts specified below, subject to Paragraph 76:

Calendar Year	**Amount**
2008	12,000 Allowances
2009	18,000 Allowances
2010	24,000 Allowances
2011, and each year thereafter	30,000 Allowances

DMG shall make the surrender of SO_2 Allowances required by this Paragraph by December 31 of each specified calendar year.

76. If the surrender of SO_2 allowances required by Paragraph 75 would result in an insufficient number of allowances being available from those allocated to the Units comprising the DMG System to meet the requirements of any Federal and/or State requirements for any DMG System unit, DMG must provide notice to the Plaintiffs of such insufficiency, including documentation of the number of SO_2 allowances so required and the Federal and/or State requirement involved. Unless EPA objects, in writing, to the amounts surrendered or to be

surrendered, the basis of the amounts surrendered or to be surrendered, or the adequacy of the documentation, DMG may reduce the number of SO_2 allowances to be surrendered under Paragraph 75 to the extent necessary to allow such DMG System Unit to satisfy the specified Federal and/or State requirement(s). If DMG has sold or traded SO_2 allowances allocated by the Administrator of EPA or a State for the year in which the surrender of allowances under Paragraph 75 would result in an insufficient number of allowances, all sold or traded allowances must be restored to DMG's account through DMG's purchase or transfer of allowances before DMG may reduce the surrender requirements of Paragraph 75 as described above.

77. Nothing in this Consent Decree is intended to preclude DMG from using SO_2 Allowances allocated to the DMG System by the Administrator of EPA under the Act, or by any State under its State Implementation Plan, to meet its own Federal and/or State Clean Air Act regulatory requirements for any Unit in the DMG System.

78. For purposes of this Subsection, the "surrender of allowances" means permanently surrendering allowances from the accounts administered by EPA for all Units in the DMG System, so that such allowances can never be used thereafter to meet any compliance requirement under the Clean Air Act, the Illinois State Implementation Plan, or this Consent Decree.

79. If any allowances required to be surrendered under this Consent Decree are transferred directly to a non-profit third party, DMG shall include a description of such transfer in the next report submitted to EPA pursuant to Section XII (Periodic Reporting) of this Consent Decree. Such report shall: (i) identify the non-profit third-party recipient(s) of the SO_2 Allowances and list the serial numbers of the transferred SO_2 Allowances; and (ii) include a

certification by the third-party recipient(s) stating that the recipient(s) will not sell, trade, or otherwise exchange any of the allowances and will not use any of the SO_2 Allowances to meet any obligation imposed by any environmental law. No later than the third periodic report due after the transfer of any SO_2 Allowances, DMG shall include a statement that the third-party recipient(s) surrendered the SO_2 Allowances for permanent surrender to EPA in accordance with the provisions of Paragraph 80 within one (1) year after DMG transferred the SO_2 Allowances to them. DMG shall not have complied with the SO_2 Allowance surrender requirements of this Paragraph until all third-party recipient(s) shall have actually surrendered the transferred SO_2 Allowances to EPA.

80. For all SO_2 Allowances surrendered to EPA, DMG or the third-party recipient(s) (as the case may be) shall first submit an SO_2 Allowance transfer request form to EPA's Office of Air and Radiation's Clean Air Markets Division directing the transfer of such SO_2 Allowances to the EPA Enforcement Surrender Account or to any other EPA account that EPA may direct in writing. As part of submitting these transfer requests, DMG or the third-party recipient(s) shall irrevocably authorize the transfer of these SO_2 Allowances and identify – by name of account and any applicable serial or other identification numbers or station names – the source and location of the SO_2 Allowances being surrendered.

81. The requirements in Paragraphs 75 and 76 of this Decree pertaining to DMG's surrender of SO_2 Allowances are permanent injunctions not subject to any termination provision of this Decree.

E. General SO_2 Provisions

82. In determining Emission Rates for SO_2, DMG shall use CEMS in accordance with those reference methods specified in 40 C.F.R. Part 75.

VI. PM EMISSION REDUCTIONS AND CONTROLS

A. Optimization of PM Emission Controls

83. Beginning ninety (90) days after entry of this Consent Decree, and continuing thereafter, DMG shall operate each PM Control Device on each Unit within the DMG System to maximize PM emission reductions at all times when the Unit is in operation, provided that such operation of the PM Control Device is consistent with the technological limitations, manufacturer's specifications and good engineering and maintenance practices for the PM Control Device. During any periods when any section or compartment of the PM control device is not operational, DMG will minimize emissions to the extent reasonably practicable. Specifically, DMG shall, at a minimum, to the extent reasonably practicable: (a) energize each section of the ESP for each unit, where applicable, operate each compartment of the Baghouse for each unit, where applicable (regardless of whether those actions are needed to comply with opacity limits), and repair any failed ESP section or Baghouse compartment at the next planned Unit outage (or unplanned outage of sufficient length); (b) operate automatic control systems on each ESP to maximize PM collection efficiency, where applicable; (c) maintain and replace bags on each Baghouse as needed to maximize collection efficiency, where applicable; and (d) inspect for and repair during the next planned Unit outage (or unplanned outage of sufficient length) any openings in ESP casings, ductwork and expansion joints to minimize air leakage.

84. Within two hundred seventy (270) days after entry of this Consent Decree, for each DMG System Unit served by an ESP or Baghouse, DMG shall complete a PM emission control optimization study which shall recommend: the best available maintenance, repair, and operating practices and a schedule for implementation of such to optimize ESP or Baghouse availability and performance in accordance with manufacturers' specifications, the operational design of the Unit, and good engineering practices. DMG shall retain a qualified contractor to assist in the performance and completion of each study and shall implement the study's recommendations in accordance with the schedule provided for in the study, but in no event later than the next planned Unit outage or 180 days of completion of the optimization study, whichever is later. Thereafter, DMG shall maintain each ESP and Baghouse as required by the study's recommendations or other alternative actions as approved by EPA. These requirements of this Paragraph shall also apply, and these activities shall be repeated, whenever DMG makes a major change to a Unit's ESP, installs a new PM Control Device, or changes the fuel used by a Unit.

B. Installation of New PM Emission Controls

85. No later than the dates set forth in the Table below for Baldwin Units 1, 2 and 3 and Havana Unit 6, and continuing thereafter, DMG shall not operate the specified Unit unless and until it has installed and commenced operation of a Baghouse on each such Unit so as to achieve and maintain a PM emissions rate of not greater than 0.015 lb/mmBTU.

Unit	Date
First Baldwin Unit (i.e., any of Baldwin Units 1, 2 or 3)	December 31, 2010
Second Baldwin Unit (i.e., either of the 2 remaining Baldwin Units)	December 31, 2011
Third Baldwin Unit (i.e., the remaining Baldwin Unit)	December 31, 2012
Havana Unit 6	December 31, 2012

C. Upgrade of Existing PM Emission Controls

86. At each Unit listed below, no later than the dates specified, and continuing thereafter, DMG shall operate ESPs or alternative PM control equipment at the following Units to achieve and maintain a PM emissions rate of not greater than 0.030 lb/mmBTU:

Unit	Date
Havana Unit 6	December 31, 2005
1st Wood River Unit (i.e., either of Wood River Units 4 or 5)	December 31, 2005
1st Hennepin Unit (i.e., either of Hennepin Units 1 or 2)	December 31, 2006
2nd Wood River Unit (i.e., the remaining Wood River Unit)	December 31, 2007
2nd Hennepin Unit (i.e., the remaining Hennepin Unit)	December 31, 2010
1st Vermilion Unit (i.e., either of Vermilion Units 1 or 2)	December 31, 2010
2nd Vermilion Unit (i.e., the remaining Vermilion Unit)	December 31, 2010

In the alternative and in lieu of demonstrating compliance with the PM emission rate applicable under this Paragraph, DMG may elect to undertake an upgrade of the existing PM emissions control equipment for any such Unit based on a Pollution Control Equipment Upgrade Analysis for that Unit. The preparation, submission, and implementation of such Pollution Control Equipment Upgrade Analysis shall be undertaken and completed in accordance with the compliance schedules and procedures as specified in Paragraph 88.

87. DMG shall operate each ESP (on Units without a Baghouse) and each Baghouse in the DMG System at all times when the Unit it serves is in operation, provided that such operation of the ESP or Baghouse is consistent with the technological limitations, manufacturers' specifications, and good engineering and maintenance practices for the ESP or Baghouse. During any such period in which the ESP or Baghouse is not operational, DMG will minimize emissions to the extent reasonably practicable. Notwithstanding the foregoing sentence, DMG shall not be required to operate an ESP on any Unit on which a Baghouse is installed and operating, unless DMG operated the ESP during the immediately preceding stack test required by Paragraph 89.

88. For each Unit in the DMG System for which DMG does not elect to meet a PM Emission Rate of 0.030 lb/mmBTU as required by Paragraph 86, DMG shall prepare, submit, and implement a Pollution Control Equipment Upgrade Analysis in accordance with this Paragraph. Such Pollution Control Equipment Upgrade Analysis shall include proposed upgrades to the Unit's existing PM Control Devices and a proposed alternate PM Emission Rate that the Unit shall meet upon completion of such upgrade. DMG shall deliver such Pollution Control Equipment Upgrade Analysis to EPA and the State of Illinois for approval pursuant to

Section XIII (Review and Approval of Submittals) of this Consent Decree at least 24 months prior to the deadlines set forth in Paragraph 86 for each such Unit, unless those deadlines are less than 24 months after the date of entry of this Decree. In those cases only, (a) the Analysis shall be delivered within 180 days of entry of this Decree, and (b) so long as DMG timely submits the Analysis, any deadline for implementing a PM Emission Control Equipment Upgrade may be extended in accordance with the provisions of subparagraph (c) below.

a. In conducting the Pollution Control Equipment Upgrade Analysis for any Unit, DMG shall consider all commercially available control technologies, except that DMG need not consider any of the following PM control measures:

   1. the complete replacement of the existing ESP with a new ESP, FGD, or Baghouse, or

   2. the upgrade of the existing ESP controls through the installation of any supplemental PM pollution control device if the costs of such upgrade are equal to or greater than the costs of a replacement ESP, FGD, or Baghouse (on a total dollar-per-ton-of-pollutant-removed basis).

b. With each Pollution Control Equipment Upgrade Analysis delivered to EPA and the State of Illinois, DMG shall simultaneously deliver all documents that were considered in preparing such Pollution Control Equipment Upgrade Analysis. DMG shall retain a qualified contractor to assist in the performance and completion of each Pollution Control Equipment Upgrade Analysis.

c. Beginning one (1) year after EPA and the State of Illinois approve the recommendation(s) made in a Pollution Control Equipment Upgrade Analysis for

a Unit, DMG shall not operate that Unit unless all equipment called for in the recommendation(s) of the Pollution Control Equipment Upgrade Analysis has been installed. An installation period longer than one year may be allowed if DMG makes such a request in the Pollution Control Equipment Upgrade Analysis and EPA and the State of Illinois determine such additional time is necessary due to factors including but not limited to the magnitude of the PM control project or the need to address reliability concerns that could result from multiple Unit outages within the DMG System. Upon installation of all equipment recommended under an approved Pollution Control Equipment Upgrade Analysis, DMG shall operate such equipment in compliance with the recommendation(s) of the approved Pollution Control Equipment Upgrade Analysis, including compliance with the PM Emission Rate specified by the recommendation(s).

D. PM Emissions Monitoring

1. PM Stack Tests.

89. Beginning in calendar year 2005, and continuing in each calendar year thereafter, DMG shall conduct a PM performance test on each DMG System Unit. The annual stack test requirement imposed on each DMG System Unit by this Paragraph may be satisfied by stack tests conducted by DMG as required by its permits from the State of Illinois for any year that such stack tests are required under the permits. DMG may perform testing every other year, rather than every year, provided that two of the most recently completed test results from tests conducted in accordance with the methods and procedures specified in Paragraph 90 demonstrate that the particulate matter emissions are equal to or less than 0.015 lb/mmBTU. DMG shall

perform testing every year, rather than every other year, beginning in the year immediately following any test result demonstrating that the particulate matter emissions are greater than 0.015 lb/mmBTU.

90. The reference methods and procedures for determining compliance with PM Emission Rates shall be those specified in 40 C.F.R. Part 60, Appendix A, Method 5, or an alternative method that is promulgated by EPA, requested for use herein by DMG, and approved for use herein by EPA and the State of Illinois. Use of any particular method shall conform to the EPA requirements specified in 40 C.F.R. Part 60, Appendix A and 40 C.F.R. § 60.48a (b) and (e), or any federally approved method contained in the Illinois State Implementation Plan. DMG shall calculate the PM Emission Rates from the stack test results in accordance with 40 C.F.R. § 60.8(f). The results of each PM stack test shall be submitted to EPA and the State of Illinois within 45 days of completion of each test.

2. PM CEMS

91. DMG shall install and operate PM CEMS in accordance with Paragraphs 92 through 96. Each PM CEMS shall comprise a continuous particle mass monitor measuring particulate matter concentration, directly or indirectly, on an hourly average basis and a diluent monitor used to convert the concentration to units of lb/mmBTU. DMG shall maintain, in an electronic database, the hourly average emission values produced by all PM CEMS in lb/mmBTU. DMG shall use reasonable efforts to keep each PM CEMS running and producing data whenever any Unit served by the PM CEMS is operating.

92. Within nine (9) months after entry of this Consent Decree, but in any case no later than June 30, 2006, DMG shall submit to EPA and the State of Illinois for review and

approval pursuant to Section XIII (Review and Approval of Submittals) of this Consent Decree (a) a plan for the installation and certification of each PM CEMS; and (b) a proposed Quality Assurance/Quality Control ("QA/QC") protocol that shall be followed in calibrating such PM CEMS. In developing both the plan for installation and certification of the PM CEMS and the QA/QC protocol, DMG shall use the criteria set forth in EPA's Amendments to Standards of Performance for New Stationary Sources: Monitoring Requirements, 69 Fed. Reg. 1786 (January 12, 2004) ("P.S. 11"). EPA and the State of Illinois shall expeditiously review such submissions. Following approval by EPA and the State of Illinois of the protocol, DMG shall thereafter operate each PM CEMS in accordance with the approved protocol.

93. No later than the dates specified below, DMG shall install, certify, and operate PM CEMS on four (4) Units, stacks or common stacks in accordance with the following schedule:

STACK	**DATE TO COMMENCE OPERATION OF PM CEMS**
1st CEM on any DMG System Unit not scheduled to receive an FGD	December 31, 2006
2nd CEM on any DMG System Unit not scheduled to receive an FGD	December 31, 2007
3rd CEM on any DMG System Unit scheduled to receive an FGD	December 31, 2011
4th CEM on any DMG System Unit scheduled to receive an FGD	December 31, 2012

94. No later than ninety (90) days after DMG begins operation of the PM CEMS, DMG shall conduct tests of each PM CEMS to demonstrate compliance with the PM CEMS installation and certification plan submitted to and approved by EPA and the State of Illinois in accordance with Paragraph 92.

95. DMG shall operate the PM CEMS for at least two (2) years on each of the Units specified in Paragraph 93. After two (2) years of operation, DMG shall not be required to continue operating the PM CEMS on any such Units if EPA determines that operation of the PM CEMS is no longer feasible. Operation of a PM CEMS shall be considered no longer feasible if (a) the PM CEMS cannot be kept in proper condition for sufficient periods of time to produce reliable, adequate, or useful data consistent with the QA/QC protocol; or (b) DMG demonstrates that recurring, chronic, or unusual equipment adjustment or servicing needs in relation to other types of continuous emission monitors cannot be resolved through reasonable expenditures of resources. If EPA determines that DMG has demonstrated pursuant to this Paragraph that operation is no longer feasible, DMG shall be entitled to discontinue operation of and remove the PM CEMS.

3. PM Reporting

96. Following the installation of each PM CEMS, DMG shall begin and continue to report to EPA, the State of Illinois, and the Citizen Plaintiffs, pursuant to Section XII (Periodic Reporting), the data recorded by the PM CEMS, expressed in lb/mmBTU on a 3-hour rolling average basis in electronic format, as required by Paragraph 91.

E. General PM Provisions

97. Nothing in this Consent Decree is intended to, or shall, alter or waive any applicable law (including any defenses, entitlements, challenges, or clarifications related to the Credible Evidence Rule, 62 Fed. Reg. 8315 (Feb. 27, 1997)) concerning the use of data for any purpose under the Act.

VII. PROHIBITION ON NETTING CREDITS OR OFFSETS FROM REQUIRED CONTROLS

98. Emission reductions that result from actions to be taken by DMG after entry of this Consent Decree to comply with the requirements of this Consent Decree shall not be considered as a creditable contemporaneous emission decrease for the purpose of obtaining a netting credit under the Clean Air Act's Nonattainment NSR and PSD programs.

99. The limitations on the generation and use of netting credits or offsets set forth in the previous Paragraph 98 do not apply to emission reductions achieved by DMG System Units that are greater than those required under this Consent Decree. For purposes of this Paragraph, emission reductions from a DMG System Unit are greater than those required under this Consent Decree if, for example, they result from DMG compliance with federally enforceable emission limits that are more stringent than those limits imposed on DMG System Units under this Consent Decree and under applicable provisions of the Clean Air Act or the Illinois State Implementation Plan.

100. Nothing in this Consent Decree is intended to preclude the emission reductions generated under this Consent Decree from being considered by the State of Illinois or EPA as creditable contemporaneous emission decreases for the purpose of attainment demonstrations

submitted pursuant to § 110 of the Act, 42 U.S.C. § 7410, or in determining impacts on NAAQS, PSD increment, or air quality related values, including visibility, in a Class I area.

VIII. ENVIRONMENTAL MITIGATION PROJECTS

101. DMG shall implement the Environmental Mitigation Projects ("Projects") described in Appendix A to this Decree in compliance with the approved plans and schedules for such Projects and other terms of this Consent Decree. DMG shall submit plans for the Projects to the Plaintiffs for review and approval pursuant to Section XIII (Review and Approval of Submittals) of this Consent Decree in accordance with the schedules set forth in Appendix A. In implementing the Projects, DMG shall spend no less than $15 million in Project Dollars on or before December 31, 2007. DMG shall maintain, and present to the Plaintiffs upon request, all documents to substantiate the Project Dollars expended and shall provide these documents to the Plaintiffs within thirty (30) days of a request by any of the Plaintiffs for the documents.

102. All plans and reports prepared by DMG pursuant to the requirements of this Section of the Consent Decree and required to be submitted to EPA shall be publicly available from DMG without charge.

103. DMG shall certify, as part of each plan submitted to the Plaintiffs for any Project, that DMG is not otherwise required by law to perform the Project described in the plan, that DMG is unaware of any other person who is required by law to perform the Project, and that DMG will not use any Project, or portion thereof, to satisfy any obligations that it may have under other applicable requirements of law, including any applicable renewable portfolio standards.

104. DMG shall use good faith efforts to secure as much benefit as possible for the Project Dollars expended, consistent with the applicable requirements and limits of this Consent Decree.

105. If DMG elects (where such an election is allowed) to undertake a Project by contributing funds to another person or entity that will carry out the Project in lieu of DMG, but not including DMG's agents or contractors, that person or instrumentality must, in writing: (a) identify its legal authority for accepting such funding; and (b) identify its legal authority to conduct the Project for which DMG contributes the funds. Regardless of whether DMG elected (where such election is allowed) to undertake a Project by itself or to do so by contributing funds to another person or instrumentality that will carry out the Project, DMG acknowledges that it will receive credit for the expenditure of such funds as Project Dollars only if DMG demonstrates that the funds have been actually spent by either DMG or by the person or instrumentality receiving them (or, in the case of internal costs, have actually been incurred by DMG), and that such expenditures met all requirements of this Consent Decree.

106. Beginning six (6) months after entry of this Consent Decree, and continuing until completion of each Project (including any applicable periods of demonstration or testing), DMG shall provide the Plaintiffs with semi-annual updates concerning the progress of each Project.

107. Within sixty (60) days following the completion of each Project required under this Consent Decree (including any applicable periods of demonstration or testing), DMG shall submit to the Plaintiffs a report that documents the date that the Project was completed, DMG's results of implementing the Project, including the emission reductions or other environmental benefits achieved, and the Project Dollars expended by DMG in implementing the Project.

IX. CIVIL PENALTY

108. Within thirty (30) calendar days after entry of this Consent Decree, DMG shall pay to the United States a civil penalty in the amount of $9,000,000. The civil penalty shall be paid by Electronic Funds Transfer ("EFT") to the United States Department of Justice, in accordance with current EFT procedures, referencing USAO File Number 1999V00379 and DOJ Case Number 90-5-2-1-06837 and the civil action case name and case number of this action. The costs of such EFT shall be DMG's responsibility. Payment shall be made in accordance with instructions provided to DMG by the Financial Litigation Unit of the U.S. Attorney's Office for the Southern District of Illinois. Any funds received after 2:00 p.m. EDT shall be credited on the next business day. At the time of payment, DMG shall provide notice of payment, referencing the USAO File Number, the DOJ Case Number, and the civil action case name and case number, to the Department of Justice and to EPA in accordance with Section XIX (Notices) of this Consent Decree.

109. Failure to timely pay the civil penalty shall subject DMG to interest accruing from the date payment is due until the date payment is made at the rate prescribed by 28 U.S.C. § 1961, and shall render DMG liable for all charges, costs, fees, and penalties established by law for the benefit of a creditor or of the United States in securing payment.

110. Payments made pursuant to this Section are penalties within the meaning of Section 162(f) of the Internal Revenue Code, 26 U.S.C. § 162(f), and are not tax-deductible expenditures for purposes of federal law.

X. RELEASE AND COVENANT NOT TO SUE FOR ILLINOIS POWER COMPANY

111. Upon entry of this Decree, each of the Plaintiffs hereby forever releases Illinois Power Company from, and covenants not to sue Illinois Power Company for, any and all civil claims, causes of action, and liability under the Clean Air Act and/or the Illinois Environmental Protection Act that such Plaintiffs could assert (whether such claims, causes of action, and liability are, were, or ever will be characterized as known or unknown, asserted or unasserted, liquidated or contingent, accrued or unaccrued), where such claims, causes of action, and liability are based on any modification, within the meaning of the Clean Air Act and/or the Illinois Environmental Protection Act, undertaken at any time before lodging of this Decree at any DMG System Unit, including and without limitation all such claims, causes of action, and liability asserted, or that could have been asserted, against Illinois Power Company by the United States, the State of Illinois and/or the Citizen Plaintiffs in the lawsuit styled United States of America, et al. v. Illinois Power Company and Dynegy Midwest Generation, Inc., Civil Action No. 99-833-MJR and all such civil claims, causes of action, and liability asserted or that could have been or could be asserted under any or all of the following statutory and/or regulatory provisions:

a. Parts C or D of Subchapter I of the Clean Air Act,

b. Section 111 of the Clean Air Act and 40 C.F.R. Section 60.14,

c. The federally approved and enforceable Illinois State Implementation Plan, but only insofar as such claims were alleged in the third amended complaint filed in the lawsuit so styled,

d. Sections 502(a) and 504(a) of the Clean Air Act, but only to the extent that such claims are based on Illinois Power's failure to obtain an operating permit that reflects applicable requirements imposed under Parts C or D of Subchapter I, or Section 111, of the Clean Air Act,

e. Sections 9 and 9.1 of the Illinois Environmental Protection Act, 415 ILCS 5/9 and 9.1, all applicable regulations promulgated thereunder, and all relevant prior versions of such statute and regulations, and

f. Section 39.5 of the Illinois Environmental Protection Act, 415 ILCS 5/39.5, and all applicable regulations promulgated thereunder, and all relevant prior versions of such statutes and regulations, but only to the extent that such claims are based on Illinois Power's failure to obtain an operating permit that reflects applicable requirements imposed under Sections 9 and 9.1 of the Illinois Environmental Protection Act, 415 ILCS 5/9 and 9.1,

where such claims, causes of actions and liability are based on any modification, within the meaning of the Clean Air Act and/or the Illinois Environmental Protection Act, undertaken at any time before lodging of this Decree at any DMG System Unit. As to Illinois Power Company, such resolved claims shall not be subject to the Bases for Pursuing Resolved Claims set forth in Section XI, Subsection B, of this Consent Decree.

112. In accordance with Paragraph 171 of this Decree, in the event that Illinois Power acquires an Ownership Interest in, or becomes an operator (as that term is used and interpreted under the Clean Air Act) of, any DMG System Unit, this release shall become void with respect

to the Unit(s) to which the Ownership Interest applies when and to the extent specified in Paragraph 171.

XI. RESOLUTION OF PLAINTIFFS' CIVIL CLAIMS AGAINST DMG

A. RESOLUTION OF PLAINTIFFS' CIVIL CLAIMS

113. Claims Based on Modifications Occurring Before the Lodging of Decree. Entry of this Decree shall resolve all civil claims of the Plaintiffs against DMG under any or all of:

a. Parts C or D of Subchapter I of the Clean Air Act,

b. Section 111 of the Clean Air Act and 40 C.F.R. Section 60.14,

c. The federally approved and enforceable Illinois State Implementation Plan, but only insofar as such claims were alleged in the third amended complaint filed in the lawsuit styled United States of America, et al. v. Illinois Power Company and Dynegy Midwest Generation, Inc., Civil Action No. 99-833-MJR,

d. Sections 502(a) and 504(a) of the Clean Air Act, but only to the extent that such claims are based on DMG's or Illinois Power's failure to obtain an operating permit that reflects applicable requirements imposed under Parts C or D of Subchapter I, or Section 111, of the Clean Air Act,

e. Sections 9 and 9.1 of the Illinois Environmental Protection Act, 415 ILCS 5/9 and 9.1, all applicable regulations promulgated thereunder, and all relevant prior versions of such statute and regulations, and

f. Section 39.5 of the Illinois Environmental Protection Act, 415 ILCS 5/39.5, and all applicable regulations promulgated thereunder, and all relevant prior versions

of such statutes and regulations, but only to the extent that such claims are based on Illinois Power's failure to obtain an operating permit that reflects applicable requirements imposed under Sections 9 and 9.1 of the Illinois Environmental Protection Act, 415 ILCS 5/9 and 9.1,

that arose from any modifications commenced at any DMG System Unit prior to the date of lodging of this Decree, including but not limited to those modifications alleged in the Complaints filed in this civil action.

114. Claims Based on Modifications After the Lodging of Decree. As to DMG, entry of this Decree also shall resolve all civil claims of the Plaintiffs against DMG for pollutants regulated under Parts C or D of Subchapter I of the Clean Air Act, and under regulations promulgated thereunder as of the date of lodging of this Decree, where such claims are based on a modification completed before December 31, 2015 and:

a. commenced at any DMG System unit after lodging of this Decree; or

b. that this Consent Decree expressly directs DMG to undertake.

The term "modification" as used in this Paragraph 114 shall have the meaning that term is given under the Clean Air Act and under the regulations promulgated thereunder as of July 31, 2003.

115. Reopeners. The Resolution of the Plaintiffs' Civil Claims against DMG, as provided by this Subsection A, is subject to the provisions of Subsection B of this Section.

B. PURSUIT OF PLAINTIFFS' CIVIL CLAIMS OTHERWISE RESOLVED

116. Bases for Pursuing Resolved Claims Across DMG System. If DMG violates System-Wide Annual Tonnage Limitations for NO_x required pursuant to Paragraph 57, the System-Wide Annual Tonnage Limitations for SO_2 required pursuant to Paragraph 73, or

operates a Unit more than ninety days past an installation date without completing the required installation or upgrade and commencing operation of any emission control device required pursuant to Paragraphs 51, 54, 66, or 85, then the Plaintiffs may pursue any claim at any DMG System Unit that is otherwise resolved under Subsection A (Resolution of Plaintiffs' Civil Claims), subject to (a) and (b) below.

a. For any claims based on modifications undertaken at an Other Unit (i.e., any Unit of the DMG System that is not an Improved Unit for the pollutant in question), claims may be pursued only where the modification(s) on which such claim is based was commenced within the five (5) years preceding the violation or failure specified in this Paragraph.

b. For any claims based on modifications undertaken at an Improved Unit, claims may be pursued only where the modification(s) on which such claim is based was commenced (1) after lodging of the Consent Decree and (2) within the five years preceding the violation or failure specified in this Paragraph.

117. Additional Bases for Pursuing Resolved Claims for Modifications at an Improved Unit. Solely with respect to Improved Units, the Plaintiffs may also pursue claims arising from a modification (or collection of modifications) at an Improved Unit that have otherwise been resolved under Subsection A (Resolution of Plaintiffs' Civil Claims), if the modification (or collection of modifications) at the Improved Unit on which such claims are based (a) was commenced after lodging of this Consent Decree, and (b) individually (or collectively) increased the maximum hourly emission rate of that Unit for NO_x or SO_2 (as measured by 40 C.F.R. § 60.14 (b) and (h)) by more than ten percent (10%).

118. Additional Bases for Pursuing Resolved Claims for Modifications at an Other Unit. a. Solely with respect to Other Units, the Plaintiffs may also pursue claims arising from a modification (or collection of modifications) at an Other Unit that have otherwise been resolved under Subsection A (Resolution of Plaintiffs' Civil Claims), if the modification (or collection of modifications) at the Other Unit on which the claim is based was commenced within the five (5) years preceding any of the following events:

1. a modification (or collection of modifications) at such Other Unit commenced after lodging of this Consent Decree increases the maximum hourly emission rate for such Other Unit for the relevant pollutant (NO_x or SO_2) (as measured by 40 C.F.R. § 60.14(b) and (h));

2. the aggregate of all Capital Expenditures made at such Other Unit (a) exceed $150/KW on the Unit's Boiler Island (based on the generating capacities identified in Paragraph 14) during the period from the date of lodging of this Decree through December 31, 2010, provided that Capital Expenditures made solely for the conversion of Vermilion Units 1 and 2 to low sulfur coal through the earlier of entry of this Consent Decree or September 30, 2005, shall be excluded; or (b) exceed $125/KW on the Unit's Boiler Island (based on the generating capacities identified in Paragraph 14) during the period from January 1, 2011 through December 31, 2015. (Capital Expenditures shall be measured in calendar year 2004

constant dollars, as adjusted by the McGraw-Hill Engineering News-Record Construction Cost Index); or

3. a modification (or collection of modifications) at such Other Unit commenced after lodging of this Consent Decree results in an emissions increase of NO_x and/or SO_2 at such Other Unit, and such increase:

(i) presents, by itself, or in combination with other emissions or sources, "an imminent and substantial endangerment" within the meaning of Section 303 of the Act, 42 U.S.C. §7603;

(ii) causes or contributes to violation of a NAAQS in any Air Quality Control Area that is in attainment with that NAAQS;

(iii) causes or contributes to violation of a PSD increment; or

(iv) causes or contributes to any adverse impact on any formally-recognized air quality and related values in any Class I area.

4. The introduction of any new or changed NAAQS shall not, standing alone, provide the showing needed under Paragraph 113, Subparagraphs (3)(ii) or (3)(iii), to pursue any claim for a modification at an Other Unit resolved under Subsection B of this Section.

b. Solely with respect to Other Units at the plants listed below, the Plaintiffs may also pursue claims arising from a modification (or collection of modifications) at such Other Unit commenced after lodging of this Consent Decree if such modification (or collection of modifications) results in an emissions increase of

NO_x and/or SO_2 at such Other Unit, and such increase causes the emissions at the Plant at issue to exceed the Plant-Wide Annual Tonnage Emission Levels listed below:

Unit	**SO_2 Tons Limit**	**NO_X Tons Limit**
Hennepin	9,050	2,650
Vermillion	17,370 (in 2005) 5,650 (in 2006 and thereafter)	3,360
Wood River	13,700	3,100

XII. PERIODIC REPORTING

119. Within one hundred eighty (180) days after each date established by this Consent Decree for DMG to achieve and maintain a certain PM Emission Rate at any DMG System Unit, DMG shall conduct a performance test for PM that demonstrates compliance with the Emission Rate required by this Consent Decree. Within forty-five (45) days of each such performance test, DMG shall submit the results of the performance test to EPA, the State of Illinois, and the Citizen Plaintiffs at the addresses specified in Section XIX (Notices) of this Consent Decree.

120. Beginning thirty (30) days after the end of the second full calendar quarter following the entry of this Consent Decree, and continuing on a semi-annual basis until December 31, 2015, and in addition to any other express reporting requirement in this Consent Decree, DMG shall submit to EPA, the State of Illinois, and the Citizen Plaintiffs a progress report.

121. The progress report shall contain the following information:

a. all information necessary to determine compliance with the requirements of the following Paragraphs of this Consent Decree: Paragraphs 51, 52, 53, 54, and 57 concerning NO_x emissions; Paragraphs 66, 70, 71, 72 and 73 concerning SO_2 emissions; Paragraphs 83, 84, 85, 86, 88 (if applicable), 89, 91, 93, and 94 concerning PM emissions;

b. documentation of any Capital Expenditures made, during the period covered by the progress report, solely for the conversion of Vermilion Units 1 and 2 to low sulfur coal, but excluded from the aggregate of Capital Expenditures pursuant to Paragraph 118(a)(2);

c. all information relating to emission allowances and credits that DMG claims to have generated in accordance with Paragraph 61 through compliance beyond the requirements of this Consent Decree; and

d. all information indicating that the installation and commencement of operation for a pollution control device may be delayed, including the nature and cause of the delay, and any steps taken by DMG to mitigate such delay.

122. In any periodic progress report submitted pursuant to this Section, DMG may incorporate by reference information previously submitted under its Title V permitting requirements, provided that DMG attaches the Title V permit report, or the relevant portion thereof, and provides a specific reference to the provisions of the Title V permit report that are responsive to the information required in the periodic progress report.

123. In addition to the progress reports required pursuant to this Section, DMG shall provide a written report to EPA, the State of Illinois, and the Citizen Plaintiffs of any violation of

the requirements of this Consent Decree within fifteen (15) calendar days of when DMG knew or should have known of any such violation. In this report, DMG shall explain the cause or causes of the violation and all measures taken or to be taken by DMG to prevent such violations in the future.

124. Each DMG report shall be signed by DMG's Vice President of Environmental Services or his or her equivalent or designee of at least the rank of Vice President, and shall contain the following certification:

> This information was prepared either by me or under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my evaluation, or the direction and my inquiry of the person(s) who manage the system, or the person(s) directly responsible for gathering the information, I hereby certify under penalty of law that, to the best of my knowledge and belief, this information is true, accurate, and complete. I understand that there are significant penalties for submitting false, inaccurate, or incomplete information to the United States.

125. If any SO_2 Allowances are surrendered to any third party pursuant to this Consent Decree, the third party's certification pursuant to Paragraph 79 shall be signed by a managing officer of the third party and shall contain the following language:

> I certify under penalty of law that,_____ [name of third party] will not sell, trade, or otherwise exchange any of the allowances and will not use any of the allowances to meet any obligation imposed by any environmental law. I understand that there are significant penalties for submitting false, inaccurate, or incomplete information to the United States.

XIII. REVIEW AND APPROVAL OF SUBMITTALS

126. DMG shall submit each plan, report, or other submission required by this Decree to the Plaintiff(s) specified whenever such a document is required to be submitted for review or approval pursuant to this Consent Decree. The Plaintiff(s) to whom the report is submitted, as required, may approve the submittal or decline to approve it and provide written comments

explaining the bases for declining such approval. Such Plaintiff(s) will endeavor to coordinate their comments into one document when explaining their bases for declining such approval. Within sixty (60) days of receiving written comments from any of the Plaintiffs, DMG shall either: (a) revise the submittal consistent with the written comments and provide the revised submittal to the Plaintiffs; or (b) submit the matter for dispute resolution, including the period of informal negotiations, under Section XVI (Dispute Resolution) of this Consent Decree.

127. Upon receipt of EPA's final approval of the submittal, or upon completion of the submittal pursuant to dispute resolution, DMG shall implement the approved submittal in accordance with the schedule specified therein or another EPA-approved schedule.

XIV. STIPULATED PENALTIES

128. For any failure by DMG to comply with the terms of this Consent Decree, and subject to the provisions of Sections XV (Force Majeure) and XVI (Dispute Resolution), DMG shall pay, within thirty (30) days after receipt of written demand to DMG by the United States, the following stipulated penalties to the United States:

Consent Decree Violation	**Stipulated Penalty**
a. Failure to pay the civil penalty as specified in Section IX (Civil Penalty) of this Consent Decree	$10,000 per day
b. Failure to comply with any applicable 30-Day Rolling Average Emission Rate for NO_x or SO_2 or Emission Rate for PM, where the violation is less than 5% in excess of the limits set forth in this Consent Decree	$2,500 per day per violation
c. Failure to comply with any applicable 30-Day Rolling Average Emission Rate for NO_x or SO_2 or Emission Rate for PM, where the violation is equal to or greater than 5% but less than 10% in excess of the limits set forth in this Consent Decree	$5,000 per day per violation

d. Failure to comply with any applicable 30-Day Rolling Average Emission Rate for NO_x or SO_2 or Emission Rate for PM, where the violation is equal to or greater than 10% in excess of the limits set forth in this Consent Decree	$10,000 per day per violation
e. Failure to comply with the System-Wide Annual Tonnage Limits for SO_2, where the violation is less than 100 tons in excess of the limits set forth in this Consent Decree	$60,000 per calendar year, plus the surrender, pursuant to the procedures set forth in Paragraphs 79 and 80 of this Consent Decree, of SO_2 Allowances in an amount equal to two times the number of tons by which the limitation was exceeded
f. Failure to comply with the System-Wide Annual Tonnage Limits for SO_2, where the violation is equal to or greater than 100 tons in excess of the limits set forth in this Consent Decree	$120,000 per calendar year, plus the surrender, pursuant to the procedures set forth in Paragraphs 79 and 80 of this Consent Decree, of SO_2 Allowances in an amount equal to two times the number of tons by which the limitation was exceeded
g. Failure to comply with the System-Wide Annual Tonnage Limits for NO_x, where the violation is less than 100 tons in excess of the limits set forth in this Consent Decree	$60,000 per calendar year, plus the surrender of NO_x Allowances in an amount equal to two times the number of tons by which the limitation was exceeded
h. Failure to comply with the System-Wide Annual Tonnage Limits for NO_x, where the violation is equal to or greater than 100 tons in excess of the limits set forth in this Consent Decree	$120,000 per calendar year, plus the surrender of NO_x Allowances in an amount equal to two times the number of tons by which the limitation was exceeded
i. Operation of a Unit required under this Consent Decree to be equipped with any NO_x, SO_2, or PM control device without the operation of such device, as required under this Consent Decree	$10,000 per day per violation during the first 30 days, $27,500 per day per violation thereafter
j. Failure to install or operate CEMS as required in this Consent Decree	$1,000 per day per violation

k. Failure to conduct performance tests of PM emissions, as required in this Consent Decree	$1,000 per day per violation
l. Failure to apply for any permit required by Section XVII	$1,000 per day per violation
m. Failure to timely submit, modify, or implement, as approved, the reports, plans, studies, analyses, protocols, or other submittals required by this Consent Decree	$750 per day per violation during the first ten days, $1,000 per day per violation thereafter
n. Using, selling or transferring NO_x Allowances except as permitted by Paragraphs 60 and 61	the surrender of NO_x Allowances in an amount equal to four times the number of NO_x Allowances used, sold, or transferred in violation of this Consent Decree
o. Failure to surrender SO_2 Allowances as required by Paragraph 75	(a) $27,500 per day plus (b) $1,000 per SO_2 Allowance not surrendered
p. Failure to demonstrate the third-party surrender of an SO_2 Allowance in accordance with Paragraph 79 and 80	$2,500 per day per violation
q. Failure to undertake and complete any of the Environmental Mitigation Projects in compliance with Section VIII (Environmental Mitigation Projects) of this Consent Decree	$1,000 per day per violation during the first 30 days, $5,000 per day per violation thereafter
r. Any other violation of this Consent Decree	$1,000 per day per violation

129. Violation of an Emission Rate that is based on a 30-Day Rolling Average is a violation on every day on which the average is based. Where a violation of a 30-Day Rolling Average Emission Rate (for the same pollutant and from the same source) recurs within periods of less than thirty (30) days, DMG shall not pay a daily stipulated penalty for any day of the recurrence for which a stipulated penalty has already been paid.

130. In any case in which the payment of a stipulated penalty includes the surrender of SO_2 Allowances, the provisions of Paragraph 76 shall not apply.

131. All stipulated penalties shall begin to accrue on the day after the performance is due or on the day a violation occurs, whichever is applicable, and shall continue to accrue until performance is satisfactorily completed or until the violation ceases, whichever is applicable. Nothing in this Consent Decree shall prevent the simultaneous accrual of separate stipulated penalties for separate violations of this Consent Decree.

132. DMG shall pay all stipulated penalties to the United States within thirty (30) days of receipt of written demand to DMG from the United States, and shall continue to make such payments every thirty (30) days thereafter until the violation(s) no longer continues, unless DMG elects within 20 days of receipt of written demand to DMG from the United States to dispute the accrual of stipulated penalties in accordance with the provisions in Section XVI (Dispute Resolution) of this Consent Decree.

133. Stipulated penalties shall continue to accrue as provided in accordance with Paragraph 128 during any dispute, with interest on accrued stipulated penalties payable and calculated at the rate established by the Secretary of the Treasury, pursuant to 28 U.S.C. § 1961, but need not be paid until the following:

a. If the dispute is resolved by agreement, or by a decision of Plaintiffs pursuant to Section XVI (Dispute Resolution) of this Consent Decree that is not appealed to the Court, accrued stipulated penalties agreed or determined to be owing, together with accrued interest, shall be paid within thirty (30) days of the effective date of the agreement or of the receipt of Plaintiffs' decision;

b. If the dispute is appealed to the Court and Plaintiffs prevail in whole or in part, DMG shall, within sixty (60) days of receipt of the Court's decision or order, pay

all accrued stipulated penalties determined by the Court to be owing, together with interest accrued on such penalties determined by the Court to be owing, except as provided in Subparagraph c, below;

c. If the Court's decision is appealed by any Party, DMG shall, within fifteen (15) days of receipt of the final appellate court decision, pay all accrued stipulated penalties determined to be owing, together with interest accrued on such stipulated penalties determined to be owing by the appellate court.

Notwithstanding any other provision of this Consent Decree, the accrued stipulated penalties agreed by the Plaintiffs and DMG, or determined by the Plaintiffs through Dispute Resolution, to be owing may be less than the stipulated penalty amounts set forth in Paragraph 128.

134. All stipulated penalties shall be paid in the manner set forth in Section IX (Civil Penalty) of this Consent Decree.

135. Should DMG fail to pay stipulated penalties in compliance with the terms of this Consent Decree, the United States shall be entitled to collect interest on such penalties, as provided for in 28 U.S.C. § 1961.

136. The stipulated penalties provided for in this Consent Decree shall be in addition to any other rights, remedies, or sanctions available to the United States by reason of DMG's failure to comply with any requirement of this Consent Decree or applicable law, except that for any violation of the Act for which this Consent Decree provides for payment of a stipulated penalty, DMG shall be allowed a credit for stipulated penalties paid against any statutory penalties also imposed for such violation.

XV. FORCE MAJEURE

137. For purposes of this Consent Decree, a "Force Majeure Event" shall mean an event that has been or will be caused by circumstances beyond the control of DMG, its contractors, or any entity controlled by DMG that delays compliance with any provision of this Consent Decree or otherwise causes a violation of any provision of this Consent Decree despite DMG's best efforts to fulfill the obligation. "Best efforts to fulfill the obligation" include using best efforts to anticipate any potential Force Majeure Event and to address the effects of any such event (a) as it is occurring and (b) after it has occurred, such that the delay or violation is minimized to the greatest extent possible.

138. Notice of Force Majeure Events. If any event occurs or has occurred that may delay compliance with or otherwise cause a violation of any obligation under this Consent Decree, as to which DMG intends to assert a claim of Force Majeure, DMG shall notify the Plaintiffs in writing as soon as practicable, but in no event later than fourteen (14) business days following the date DMG first knew, or by the exercise of due diligence should have known, that the event caused or may cause such delay or violation. In this notice, DMG shall reference this Paragraph of this Consent Decree and describe the anticipated length of time that the delay or violation may persist, the cause or causes of the delay or violation, all measures taken or to be taken by DMG to prevent or minimize the delay or violation, the schedule by which DMG proposes to implement those measures, and DMG's rationale for attributing a delay or violation to a Force Majeure Event. DMG shall adopt all reasonable measures to avoid or minimize such delays or violations. DMG shall be deemed to know of any circumstance which DMG, its contractors, or any entity controlled by DMG knew or should have known.

139. Failure to Give Notice. If DMG fails to comply with the notice requirements of this Section, EPA (after consultation with the State of Illinois and the Citizen Plaintiffs) may void DMG's claim for Force Majeure as to the specific event for which DMG has failed to comply with such notice requirement.

140. Plaintiffs' Response. EPA shall notify DMG in writing regarding DMG's claim of Force Majeure within twenty (20) business days of receipt of the notice provided under Paragraph 138. If EPA (after consultation with the State of Illinois and the Citizen Plaintiffs) agrees that a delay in performance has been or will be caused by a Force Majeure Event, EPA and DMG shall stipulate to an extension of deadline(s) for performance of the affected compliance requirement(s) by a period equal to the delay actually caused by the event. In such circumstances, an appropriate modification shall be made pursuant to Section XXIII (Modification) of this Consent Decree.

141. Disagreement. If EPA (after consultation with the State of Illinois and the Citizen Plaintiffs) does not accept DMG's claim of Force Majeure, or if EPA and DMG cannot agree on the length of the delay actually caused by the Force Majeure Event, the matter shall be resolved in accordance with Section XVI (Dispute Resolution) of this Consent Decree.

142. Burden of Proof. In any dispute regarding Force Majeure, DMG shall bear the burden of proving that any delay in performance or any other violation of any requirement of this Consent Decree was caused by or will be caused by a Force Majeure Event. DMG shall also bear the burden of proving that DMG gave the notice required by this Section and the burden of proving the anticipated duration and extent of any delay(s) attributable to a Force Majeure Event.

An extension of one compliance date based on a particular event may, but will not necessarily, result in an extension of a subsequent compliance date.

143. Events Excluded. Unanticipated or increased costs or expenses associated with the performance of DMG's obligations under this Consent Decree shall not constitute a Force Majeure Event.

144. Potential Force Majeure Events. The Parties agree that, depending upon the circumstances related to an event and DMG's response to such circumstances, the kinds of events listed below are among those that could qualify as Force Majeure Events within the meaning of this Section: construction, labor, or equipment delays; Malfunction of a Unit or emission control device; acts of God; acts of war or terrorism; and orders by a government official, government agency, other regulatory authority, or a regional transmission organization, acting under and authorized by applicable law, that directs DMG to supply electricity in response to a system-wide (state-wide or regional) emergency. Depending upon the circumstances and DMG's response to such circumstances, failure of a permitting authority to issue a necessary permit in a timely fashion may constitute a Force Majeure Event where the failure of the permitting authority to act is beyond the control of DMG and DMG has taken all steps available to it to obtain the necessary permit, including, but not limited to: submitting a complete permit application; responding to requests for additional information by the permitting authority in a timely fashion; and accepting lawful permit terms and conditions after expeditiously exhausting any legal rights to appeal terms and conditions imposed by the permitting authority.

145. As part of the resolution of any matter submitted to this Court under Section XVI (Dispute Resolution) of this Consent Decree regarding a claim of Force Majeure, the Plaintiffs

and DMG by agreement, or this Court by order, may in appropriate circumstances extend or modify the schedule for completion of work under this Consent Decree to account for the delay in the work that occurred as a result of any delay agreed to by the United States and the States or approved by the Court. DMG shall be liable for stipulated penalties for its failure thereafter to complete the work in accordance with the extended or modified schedule (provided that DMG shall not be precluded from making a further claim of Force Majeure with regard to meeting any such extended or modified schedule).

XVI. DISPUTE RESOLUTION

146. The dispute resolution procedure provided by this Section shall be available to resolve all disputes arising under this Consent Decree, provided that the Party invoking such procedure has first made a good faith attempt to resolve the matter with the other Party.

147. The dispute resolution procedure required herein shall be invoked by one Party giving written notice to the other Party advising of a dispute pursuant to this Section. The notice shall describe the nature of the dispute and shall state the noticing Party's position with regard to such dispute. The Party receiving such a notice shall acknowledge receipt of the notice, and the Parties in dispute shall expeditiously schedule a meeting to discuss the dispute informally not later than fourteen (14) days following receipt of such notice.

148. Disputes submitted to dispute resolution under this Section shall, in the first instance, be the subject of informal negotiations among the disputing Parties. Such period of informal negotiations shall not extend beyond thirty (30) calendar days from the date of the first meeting among the disputing Parties' representatives unless they agree in writing to shorten or extend this period. During the informal negotiations period, the disputing Parties may also

submit their dispute to a mutually agreed upon alternative dispute resolution (ADR) forum if the Parties agree that the ADR activities can be completed within the 30-day informal negotiations period (or such longer period as the Parties may agree to in writing).

149. If the disputing Parties are unable to reach agreement during the informal negotiation period, the Plaintiffs shall provide DMG with a written summary of their position regarding the dispute. The written position provided by Plaintiffs shall be considered binding unless, within forty-five (45) calendar days thereafter, DMG seeks judicial resolution of the dispute by filing a petition with this Court. The Plaintiffs may respond to the petition within forty-five (45) calendar days of filing. In their initial filings with the Court under this Paragraph, the disputing Parties shall state their respective positions as to the applicable standard of law for resolving the particular dispute.

150. The time periods set out in this Section may be shortened or lengthened upon motion to the Court of one of the Parties to the dispute, explaining the party's basis for seeking such a scheduling modification.

151. This Court shall not draw any inferences nor establish any presumptions adverse to any disputing Party as a result of invocation of this Section or the disputing Parties' inability to reach agreement.

152. As part of the resolution of any dispute under this Section, in appropriate circumstances the disputing Parties may agree, or this Court may order, an extension or modification of the schedule for the completion of the activities required under this Consent Decree to account for the delay that occurred as a result of dispute resolution. DMG shall be liable for stipulated penalties for its failure thereafter to complete the work in accordance with

the extended or modified schedule, provided that DMG shall not be precluded from asserting that a Force Majeure Event has caused or may cause a delay in complying with the extended or modified schedule.

153. The Court shall decide all disputes pursuant to applicable principles of law for resolving such disputes. In their initial filings with the Court under Paragraph 149, the disputing Parties shall state their respective positions as to the applicable standard of law for resolving the particular dispute.

XVII. PERMITS

154. Unless expressly stated otherwise in this Consent Decree, in any instance where otherwise applicable law or this Consent Decree requires DMG to secure a permit to authorize construction or operation of any device contemplated herein, including all preconstruction, construction, and operating permits required under state law, DMG shall make such application in a timely manner. EPA and the State of Illinois shall use their best efforts to review expeditiously all permit applications submitted by DMG to meet the requirements of this Consent Decree.

155. Notwithstanding the previous Paragraph, nothing in this Consent Decree shall be construed to require DMG to apply for or obtain a PSD or Nonattainment NSR permit for physical changes in, or changes in the method of operation of, any DMG System Unit that would give rise to claims resolved by Section XI. A. (Resolution of Plaintiffs' Civil Claims) of this Consent Decree.

156. When permits are required as described in Paragraph 154, DMG shall complete and submit applications for such permits to the appropriate authorities to allow time for all

legally required processing and review of the permit request, including requests for additional information by the permitting authorities. Any failure by DMG to submit a timely permit application for any Unit in the DMG System shall bar any use by DMG of Section XV (Force Majeure) of this Consent Decree, where a Force Majeure claim is based on permitting delays.

157. Notwithstanding the reference to Title V permits in this Consent Decree, the enforcement of such permits shall be in accordance with their own terms and the Act. The Title V permits shall not be enforceable under this Consent Decree, although any term or limit established by or under this Consent Decree shall be enforceable under this Consent Decree regardless of whether such term has or will become part of a Title V permit, subject to the terms of Section XXVII (Conditional Termination of Enforcement Under Decree) of this Consent Decree.

158. Within one hundred eighty (180) days after entry of this Consent Decree, DMG shall amend any applicable Title V permit application, or apply for amendments of its Title V permits, to include a schedule for all Unit-specific performance, operational, maintenance, and control technology requirements established by this Consent Decree including, but not limited to, required emission rates and the requirement in Paragraph 75 pertaining to the surrender of SO_2 Allowances.

159. Within one (1) year from the commencement of operation of each pollution control device to be installed, upgraded, or operated under this Consent Decree, DMG shall apply to amend its Title V permit for the generating plant where such device is installed to reflect all new requirements applicable to that plant, including, but not limited to, any applicable 30-Day Rolling Average Emission Rate.

160. Prior to January 1, 2015, DMG shall either: (a) apply to amend the Title V permit for each plant in the DMG System to include a provision, which shall be identical for each Title V permit, that contains the allowance surrender requirements and the System-Wide Annual Tonnage Limitations set forth in this Consent Decree; or (b) apply for amendments to the Illinois State Implementation Plan to include such requirements and limitations therein.

161. DMG shall provide the Plaintiffs with a copy of each application to amend its Title V permit for a plant within the DMG System, as well as a copy of any permit proposed as a result of such application, to allow for timely participation in any public comment opportunity.

162. If DMG sells or transfers to an entity unrelated to DMG ("Third Party Purchaser") part or all of its Ownership Interest in a Unit in the DMG System, DMG shall comply with the requirements of Section XX (Sales or Transfers of Ownership Interests) with regard to that Unit prior to any such sale or transfer unless, following any such sale or transfer, DMG remains the holder of the Title V permit for such facility.

XVIII. INFORMATION COLLECTION AND RETENTION

163. Any authorized representative of the United States or the State of Illinois, including their attorneys, contractors, and consultants, upon presentation of credentials, shall have a right of entry upon the premises of any facility in the DMG System at any reasonable time for the purpose of:

a. monitoring the progress of activities required under this Consent Decree;

b. verifying any data or information submitted to the United States in accordance with the terms of this Consent Decree;

c. obtaining samples and, upon request, splits of any samples taken by DMG or its representatives, contractors, or consultants; and

d. assessing DMG's compliance with this Consent Decree.

164. DMG shall retain, and instruct its contractors and agents to preserve, all non-identical copies of all records and documents (including records and documents in electronic form) now in its or its contractors' or agents' possession or control, and that directly relate to DMG's performance of its obligations under this Consent Decree for the following periods: (a) until December 31, 2020 for records concerning physical or operational changes undertaken in accordance with Paragraph 114; and (b) until December 31, 2017 for all other records. This record retention requirement shall apply regardless of any corporate document retention policy to the contrary.

165. All information and documents submitted by DMG pursuant to this Consent Decree shall be subject to any requests under applicable law providing public disclosure of documents unless (a) the information and documents are subject to legal privileges or protection or (b) DMG claims and substantiates in accordance with 40 C.F.R. Part 2 that the information and documents contain confidential business information.

166. Nothing in this Consent Decree shall limit the authority of the EPA or the State of Illinois to conduct tests and inspections at DMG's facilities under Section 114 of the Act, 42 U.S.C. § 7414, or any other applicable federal or state laws, regulations or permits.

XIX. NOTICES

167. Unless otherwise provided herein, whenever notifications, submissions, or communications are required by this Consent Decree, they shall be made in writing and addressed as follows:

As to the United States of America:

Chief, Environmental Enforcement Section
Environment and Natural Resources Division
U.S. Department of Justice
P.O. Box 7611, Ben Franklin Station
Washington, D.C. 20044-7611
DJ# 90-5-2-1-06837

and

Director, Air Enforcement Division
Office of Enforcement and Compliance Assurance
U.S. Environmental Protection Agency
Ariel Rios Building [2242A]
1200 Pennsylvania Avenue, N.W.
Washington, DC 20460

and

Regional Administrator
U.S. EPA- Region 5
77 W. Jackson St.
Chicago, IL 60604

and

George Czerniak, Chief, AECAB
U.S. EPA- Region 5
77 W. Jackson St. - AE-17J
Chicago, IL 60604

As to the State of Illinois:

Bureau Chief
Bureau of Air

Illinois Environmental Protection Agency
1021 North Grand Avenue East, P.O. Box 19276
Springfield, Illinois 62794-9276

and

Bureau Chief
Environmental Bureau
Illinois Attorney General's Office
500 South Second Street
Springfield, Illinois 62706

As to the Citizen Plaintiffs:

Executive Director
Environmental Law and Policy Center of the Midwest
35 East Wacker Dr. Suite 1300
Chicago, Illinois 60601-2110

As to DMG:

Vice President, Environmental Health & Safety
Dynegy Midwest Generation, Inc.
2828 North Monroe Street
Decatur, Illinois 62526

and

Executive Vice President and General Counsel
Dynegy Inc.
1000 Louisiana Street, Suite 5800
Houston, Texas 77002

As to Illinois Power Company:

Senior Vice President, General Counsel, and Secretary
Illinois Power Company
One Ameren Plaza
1901 Chouteau Avenue
St. Louis, Missouri 63166

168. All notifications, communications or submissions made pursuant to this Section shall be sent either by: (a) overnight mail or overnight delivery service, or (b) certified or registered mail, return receipt requested. All notifications, communications and transmissions (a) sent by overnight, certified or registered mail shall be deemed submitted on the date they are postmarked, or (b) sent by overnight delivery service shall be deemed submitted on the date they are delivered to the delivery service.

169. Any Party may change either the notice recipient or the address for providing notices to it by serving all other Parties with a notice setting forth such new notice recipient or address.

XX. SALES OR TRANSFERS OF OWNERSHIP INTERESTS

170. If DMG proposes to sell or transfer an Ownership Interest to an entity unrelated to DMG ("Third Party Purchaser"), it shall advise the Third Party Purchaser in writing of the existence of this Consent Decree prior to such sale or transfer, and shall send a copy of such written notification to the Plaintiffs pursuant to Section XIX (Notices) of this Consent Decree at least sixty (60) days before such proposed sale or transfer.

171. No sale or transfer of an Ownership Interest shall take place before the Third Party Purchaser and EPA have executed, and the Court has approved, a modification pursuant to Section XXIII (Modification) of this Consent Decree making the Third Party Purchaser a party to this Consent Decree and jointly and severally liable with DMG for all the requirements of this Decree that may be applicable to the transferred or purchased Ownership Interests. Should Illinois Power (or any successor thereof) become a Third Party Purchaser or an operator (as the term "operator" is used and interpreted under the Clean Air Act) of any DMG System Unit, then

the provisions in Section X of this Consent Decree (Release and Covenant Not to Sue for Illinois Power Company) that apply to Illinois Power shall no longer apply as to the DMG System Unit(s) associated with the transfer, and instead, the Resolution of Plaintiffs' Civil Claims provisions in Section XI that apply to DMG shall apply to Illinois Power with respect to such transferred Unit(s), and such changes shall be reflected in the modification to the Decree reflecting the sale or transfer of an Ownership Interest contemplated by this Paragraph.

172. This Consent Decree shall not be construed to impede the transfer of any Ownership Interests between DMG and any Third Party Purchaser so long as the requirements of this Consent Decree are met. This Consent Decree shall not be construed to prohibit a contractual allocation – as between DMG and any Third Party Purchaser of Ownership Interests – of the burdens of compliance with this Decree, provided that both DMG and such Third Party Purchaser shall remain jointly and severally liable to EPA for the obligations of the Decree applicable to the transferred or purchased Ownership Interests.

173. If EPA agrees, EPA, DMG, and the Third Party Purchaser that has become a party to this Consent Decree pursuant to Paragraph 171, may execute a modification that relieves DMG of its liability under this Consent Decree for, and makes the Third Party Purchaser liable for, all obligations and liabilities applicable to the purchased or transferred Ownership Interests. Notwithstanding the foregoing, however, DMG may not assign, and may not be released from, any obligation under this Consent Decree that is not specific to the purchased or transferred Ownership Interests, including the obligations set forth in Sections VIII (Environmental Mitigation Projects) and IX (Civil Penalty). DMG may propose and the EPA may agree to restrict the scope of the joint and several liability of any purchaser or transferee for any

obligations of this Consent Decree that are not specific to the transferred or purchased Ownership Interests, to the extent such obligations may be adequately separated in an enforceable manner.

174. Paragraphs 170 and 171 of this Consent Decree do not apply if an Ownership Interest is sold or transferred solely as collateral security in order to consummate a financing arrangement (not including a sale-leaseback), so long as DMG: a) remains the operator (as that term is used and interpreted under the Clean Air Act) of the subject DMG System Unit(s); b) remains subject to and liable for all obligations and liabilities of this Consent Decree; and c) supplies Plaintiffs with the following certification within 30 days of the sale or transfer:

> "Certification of Change in Ownership Interest Solely for Purpose of Consummating Financing. We, the Chief Executive Officer and General Counsel of Dynegy Midwest Generation, hereby jointly certify under Title 18 U.S.C. Section 1001, on our own behalf and on behalf of Dynegy Midwest Generation ("DMG"), that any change in DMG's Ownership Interest in any Unit that is caused by the sale or transfer as collateral security of such Ownership Interest in such Unit(s) pursuant to the financing agreement consummated on [insert applicable date] between DMG and [insert applicable entity]: a) is made solely for the purpose of providing collateral security in order to consummate a financing arrangement; b) does not impair DMG's ability, legally or otherwise, to comply timely with all terms and provisions of the Consent Decree entered in *United States of America, et al. v. Illinois Power Company and Dynegy Midwest Generation, Inc.*, Civil Action No. 99-833-MJR; c) does not affect DMG's operational control of any Unit covered by that Consent Decree in a manner that is inconsistent with DMG's performance of its obligations under the Consent Decree; and d) in no way affects the status of DMG's obligations or liabilities under that Consent Decree."

XXI. EFFECTIVE DATE

175. The effective date of this Consent Decree shall be the date upon which this Consent Decree is entered by the Court.

XXII. RETENTION OF JURISDICTION

176. The Court shall retain jurisdiction of this case after entry of this Consent Decree to enforce compliance with the terms and conditions of this Consent Decree and to take any action necessary or appropriate for its interpretation, construction, execution, modification, or adjudication of disputes. During the term of this Consent Decree, any Party to this Consent Decree may apply to the Court for any relief necessary to construe or effectuate this Consent Decree.

XXIII. MODIFICATION

177. The terms of this Consent Decree may be modified only by a subsequent written agreement signed by the Plaintiffs and DMG. Where the modification constitutes a material change to any term of this Decree, it shall be effective only upon approval by the Court.

XXIV. GENERAL PROVISIONS

178. This Consent Decree is not a permit. Compliance with the terms of this Consent Decree does not guarantee compliance with all applicable federal, state, or local laws or regulations. The emission rates set forth herein do not relieve the Defendants from any obligation to comply with other state and federal requirements under the Clean Air Act, including the Defendants' obligation to satisfy any state modeling requirements set forth in the Illinois State Implementation Plan.

179. This Consent Decree does not apply to any claim(s) of alleged criminal liability.

180. In any subsequent administrative or judicial action initiated by any of the Plaintiffs for injunctive relief or civil penalties relating to the facilities covered by this Consent

Decree, the Defendants shall not assert any defense or claim based upon principles of waiver, res judicata, collateral estoppel, issue preclusion, claim preclusion, or claim splitting, or any other defense based upon the contention that the claims raised by any of the Plaintiffs in the subsequent proceeding were brought, or should have been brought, in the instant case; provided, however, that nothing in this Paragraph is intended to affect the validity of Sections X (Release and Covenant Not to Sue for Illinois Power Company) and XI (Resolution of Plaintiffs' Civil Claims Against DMG).

181. Except as specifically provided by this Consent Decree, nothing in this Consent Decree shall relieve the Defendants of their obligation to comply with all applicable federal, state, and local laws and regulations. Subject to the provisions in Sections X (Release and Covenant Not to Sue for Illinois Power Company) and XI (Resolution of Plaintiffs' Civil Claims Against DMG), nothing contained in this Consent Decree shall be construed to prevent or limit the rights of the Plaintiffs to obtain penalties or injunctive relief under the Act or other federal, state, or local statutes, regulations, or permits.

182. Every term expressly defined by this Consent Decree shall have the meaning given to that term by this Consent Decree and, except as otherwise provided in this Decree, every other term used in this Decree that is also a term under the Act or the regulations implementing the Act shall mean in this Decree what such term means under the Act or those implementing regulations.

183. Nothing in this Consent Decree is intended to, or shall, alter or waive any applicable law (including but not limited to any defenses, entitlements, challenges, or

clarifications related to the Credible Evidence Rule, 62 Fed. Reg. 8314 (Feb. 24, 1997)) concerning the use of data for any purpose under the Act.

184. Each limit and/or other requirement established by or under this Decree is a separate, independent requirement.

185. Performance standards, emissions limits, and other quantitative standards set by or under this Consent Decree must be met to the number of significant digits in which the standard or limit is expressed. For example, an Emission Rate of 0.100 is not met if the actual Emission Rate is 0.101. DMG shall round the fourth significant digit to the nearest third significant digit, or the third significant digit to the nearest second significant digit, depending upon whether the limit is expressed to three or two significant digits. For example, if an actual Emission Rate is 0.1004, that shall be reported as 0.100, and shall be in compliance with an Emission Rate of 0.100, and if an actual Emission Rate is 0.1005, that shall be reported as 0.101, and shall not be in compliance with an Emission Rate of 0.100. DMG shall report data to the number of significant digits in which the standard or limit is expressed.

186. This Consent Decree does not limit, enlarge or affect the rights of any Party to this Consent Decree as against any third parties.

187. This Consent Decree constitutes the final, complete and exclusive agreement and understanding among the Parties with respect to the settlement embodied in this Consent Decree, and supercedes all prior agreements and understandings among the Parties related to the subject matter herein. No document, representation, inducement, agreement, understanding, or promise constitutes any part of this Decree or the settlement it represents, nor shall they be used in construing the terms of this Consent Decree.

188. Each Party to this action shall bear its own costs and attorneys' fees.

XXV. SIGNATORIES AND SERVICE

189. Each undersigned representative of the Parties certifies that he or she is fully authorized to enter into the terms and conditions of this Consent Decree and to execute and legally bind to this document the Party he or she represents.

190. This Consent Decree may be signed in counterparts, and such counterpart signature pages shall be given full force and effect.

191. Each Party hereby agrees to accept service of process by mail with respect to all matters arising under or relating to this Consent Decree and to waive the formal service requirements set forth in Rule 4 of the Federal Rules of Civil Procedure and any applicable Local Rules of this Court including, but not limited to, service of a summons.

XXVI. PUBLIC COMMENT

192. The Parties agree and acknowledge that final approval by the United States and entry of this Consent Decree is subject to the procedures of 28 C.F.R. § 50.7, which provides for notice of the lodging of this Consent Decree in the Federal Register, an opportunity for public comment, and the right of the United States to withdraw or withhold consent if the comments disclose facts or considerations which indicate that the Consent Decree is inappropriate, improper or inadequate. The Defendants shall not oppose entry of this Consent Decree by this Court or challenge any provision of this Consent Decree unless the United States has notified the Defendants, in writing, that the United States no longer supports entry of the Consent Decree.

XXVII. CONDITIONAL TERMINATION OF ENFORCEMENT UNDER DECREE

193. Termination as to Completed Tasks. As soon as DMG completes a construction project or any other requirement of this Consent Decree that is not ongoing or recurring, DMG may, by motion to this Court, seek termination of the provision or provisions of this Consent Decree that imposed the requirement.

194. Conditional Termination of Enforcement Through the Consent Decree. After DMG:

a. has successfully completed construction, and has maintained operation, of all pollution controls as required by this Consent Decree;

b. has obtained final Title V permits (i) as required by the terms of this Consent Decree; (ii) that cover all units in this Consent Decree; and (iii) that include as enforceable permit terms all of the Unit performance and other requirements specified in Section XVII (Permits) of this Consent Decree; and

c. certifies that the date is later than December 31, 2015;

then DMG may so certify these facts to the Plaintiffs and this Court. If the Plaintiffs do not object in writing with specific reasons within forty-five (45) days of receipt of DMG's certification, then, for any Consent Decree violations that occur after the filing of notice, the Plaintiffs shall pursue enforcement of the requirements contained in the Title V permit through the applicable Title V permit and not through this Consent Decree.

195. Resort to Enforcement under this Consent Decree. Notwithstanding Paragraph 194, if enforcement of a provision in this Decree cannot be pursued by a party under the

applicable Title V permit, or if a Decree requirement was intended to be part of a Title V Permit and did not become or remain part of such permit, then such requirement may be enforced under the terms of this Decree at any time.

XXVIII. FINAL JUDGMENT

196. Upon approval and entry of this Consent Decree by the Court, this Consent Decree shall constitute a final judgment among the Plaintiffs, DMG, and Illinois Power.

SO ORDERED, THIS _____ DAY OF _____, 200_.

_____
HONORABLE MICHAEL J. REAGAN
UNITED STATES DISTRICT COURT JUDGE

Signature Page for Consent Decree in:

United States of America
v.
Illinois Power and Dynegy Midwest Generation Inc.

FOR THE UNITED STATES OF AMERICA:

_____
THOMAS L. SANSONETTI
Assistant Attorney General
Environmental and Natural Resources Division
United States Department of Justice

_____
Nicole Veilleux
Trial Attorney
Environmental Enforcement Section
Environmental and Natural Resources Division
United States Department of Justice

_____
William Coonan
Assistant United States Attorney
Southern District of Illinois
United States Department of Justice

Signature Page for Consent Decree in:

United States of America
v.
Illinois Power Company and Dynegy Midwest Generation Inc.

_____
THOMAS V. SKINNER
Acting Assistant Administrator
Office of Enforcement and Compliance Assurance
United States Environmental Protection Agency

_____
ADAM M. KUSHNER
Acting Director, Air Enforcement Division
Office of Enforcement and Compliance Assurance
United States Environmental Protection Agency

_____
Edward J. Messina
Attorney Advisor
Air Enforcement Division
Office of Enforcement and Compliance Assurance
United States Environmental Protection Agency

Signature Page for Consent Decree in:

United States of America
v.
Illinois Power Company and Dynegy Midwest Generation Inc.

_____
Bharat Mathur
Acting Regional Administrator
U.S. Environmental Protection Agency
Region 5

_____
Mark Palermo
Associate Regional Counsel
U.S. Environmental Protection Agency
Region 5

Signature Page for Consent Decree in:

United States of America
v.
Illinois Power Company and Dynegy Midwest Generation Inc.

FOR THE STATE OF ILLINOIS
PEOPLE OF THE STATE OF ILLINOIS ex rel:

LISA MADIGAN
Attorney General of the State of Illinois

MATTHEW J. DUNN, Chief
Environmental Enforcement/Asbestos
Litigation Division

_____
by: Thomas Davis, Chief
Environmental Bureau
Assistant Attorney General

Signature Page for Consent Decree in:

United States of America
v.
Illinois Power Company and Dynegy Midwest Generation Inc.

FOR CITIZEN PLAINTIFFS:

_____
Albert Ettinger
Senior Staff Attorney
Environmental Law and Policy Center of the Midwest

Signature Page for Consent Decree in:

United States of America
v.
Illinois Power Company and Dynegy Midwest Generation Inc.

FOR DYNEGY MIDWEST GENERATION:

_____
Alec G. Dreyer
President
Dynegy Midwest Generation, Inc.

Signature Page for Consent Decree in:

United States of America
v.
Illinois Power Company and Dynegy Midwest Generation Inc.

FOR ILLINOIS POWER COMPANY:

_____
Steven R. Sullivan
Senior Vice President, General Counsel and Secretary
Illinois Power Company

APPENDIX A - MITIGATION PROJECTS REQUIREMENTS

In compliance with and in addition to the requirements in Section VIII of the Consent Decree, DMG shall comply with the requirements of this Appendix to ensure that the benefits of the environmental mitigation projects are achieved.

I. Advanced Truck Stop Electrification Project

A. Within one hundred thirty five (135) days after entry of this Consent Decree, DMG shall submit a plan to the Plaintiffs for review and approval for the completion of the installation of Advanced Truck Stop Electrification, preferably at State of Illinois owned rest areas along Illinois interstate highways in the St. Louis Metro East area (comprised of Madison, St. Clair and Monroe Counties in Illinois) or as nearby as possible. Long-haul truck drivers typically idle their engines at night at rest areas to supply heat or cooling in their sleeper cab compartments, and to maintain vehicle battery charge while electrical appliances such as TVs, computers and microwaves are in use. Modifications to rest areas to provide parking spaces with electrical power, heat and air conditioning will allow truck drivers to turn their engines off. Truck driver utilization of the Advanced Truck Stop Electrification will result in reduced idling time and therefore reduced fuel usage, reduced emissions of PM, NOx, VOCs and toxics, and reduced noise. This Project shall include, where necessary, techniques and infrastructure needed to support such project. DMG shall spend no less than $1.5 million in Project Dollars in performing this Advanced Truck Stop Electrification Project.

B. The proposed plan shall satisfy the following criteria:

1. Describe how the work or project to be performed is consistent with requirements of Section I. A., above.
2. Involve rest areas located in areas that are either in the St. Louis Metro East area (comprised of Madison, St. Clair and Monroe Counties in Illinois) or as nearby as reasonably possible.
3. Provide for the construction of Advanced Truck Stop Electrification stations with established technologies and equipment designed to reduce emissions of particulates and/or ozone precursors.
4. Account for hardware procurement and installation costs at the recipient truck stops.
5. Include a schedule for completing each portion of the project.
6. Describe generally the expected environmental benefits of the project.
7. DMG shall not profit from this project for the first five years of implementation.

C. Performance - Upon approval of plan by the Plaintiffs, DMG shall complete the mitigation project according to the approved plan and schedule, but no later than December 31, 2007.

II. Middle Fork/Vermilion Land Donation

A. Within sixty (60) days after entry of the Consent Decree, DMG shall submit a plan to the Plaintiffs for review and approval for the transfer of ownership to the State of Illinois Department of Natural Resources (IDNR), of an approximately 1135 acre parcel of land along the Middle Fork Vermilion River in Vermilion County identified as the Middle Fork/Vermilion ("Property"). The value of the Property to be donated can be fairly valued at $2.25 million. Accordingly, DMG's full and final transfer of the Property in accordance with the plan shall satisfy its requirement to spend at least $2.25 million Project Dollars to implement this project.

B. The proposed plan shall satisfy the following criteria:

1. Describe how the work or project to be performed is consistent with requirements of Section II. A., above.
2. This project entails the donation of the entire parcel of land owned by DMG (an approximately 1135 acre parcel of land) as of lodging of the Consent Decree along the East side of the Middle Fork Vermilion River in Vermilion County. The Property is located between Kickapoo State Park and the Middle Fork State Fish and Wildlife Area and Kennekuk County Park on the East side of the Middle Fork of the Vermilion River. Ownership of the Property and management of the natural resources thereon shall be transferred to IDNR so as to ensure the continued preservation and public use of the Property.
3. The plan shall include DMG's agreement to convey to IDNR, the Property, the Ancillary Structures and the Personal Property, if any, to the extent located on the Property, and to the extent owned by DMG. The plan shall include steps for resolution of all past liens, payment of all outstanding taxes, title transfer, and other such information as would be necessary to convey the Property to IDNR. In all other respects, the Property will be conveyed subject to the easements, rights-of-way and similar rights of third parties existing as of the date of the conveyance.
4. DMG shall retain its existing right to take and use the water from a stripmine lake located in the NW ¼ of Section 28, T-20_N, R-12-W, 3 P.M. and in the NE ¼ of Section 29, T-20_N, R-12-W, 3rd P.M. of Vermillion County, and an easement to access this water and to provide electrical power to pump the water.
5. DMG agrees to furnish to IDNR a current Alta/ACSM Land Title Survey of the Property prepared and certified by an Illinois registered land surveyor.
6. Describe generally the expected environmental benefit for the project.

C. Performance - Upon approval of plan by the Plaintiffs, DMG shall complete the mitigation project according to the approved plan and schedule, and convey such Property prior to the date 180 days from entry of this Consent Decree or June 30, 2006, whichever is earlier.

III. Metro East Land Acquisition and Preservation and Illinois River Projects

A. Within sixty (60) days after entry of the Consent Decree, and following consultation with Plaintiffs, including on behalf of the State of Illinois, the Illinois Department of Natural Resources, DMG shall submit a plan to the Plaintiffs for review and approval for the transfer of $2.75 million to the Illinois Conservation Foundation, 20 ILCS 880/15 (2004). The funds transferred by DMG to the Illinois Conservation Foundation shall be used for the express purpose of acquiring natural lands and habitat in the St Louis Metro East area, for acquiring and/or restoring endangered habitat along the Illinois River, and for future funding of the Illinois River Sediment Removal and Beneficial Reuse Initiative, administered by the Waste Management Resource Center of IDNR. In addition, to the extent possible, the funding shall be utilized to enhance existing wetlands and create new wetlands restoration projects at sites along the Illinois River between DMG's Havana Station and the Hennepin Station, and provide for public use of acquired areas in a manner consistent with the ecology and historic uses of the area. Further, to the extent possible, the funding shall enable the removal and transport of high quality soil sediments from the Illinois River bottom to end users, including State fish and wildlife areas, a local environmental remediation project, and other projects deemed beneficial by plaintiffs. Any properties acquired through funding of this project shall be placed in the permanent ownership of the State of Illinois and preserved for public use by IDNR.

B. The proposed plan shall satisfy the following criteria:

1. Describe how the work or project to be performed is consistent with requirements of Section III. A., above.
2. Include a schedule for completing the funding of each portion of the project.
3. Describe generally the expected environmental benefit for the project.

C. Performance - Upon approval of plan by the Plaintiffs, DMG shall complete the mitigation project according to the approved plan and schedule, but no later than December 31, 2007.

IV. Vermilion Power Station Mercury Control Project

A. Within sixty (60) days of entry of the Consent Decree, DMG shall submit a plan to the Plaintiffs for review and approval for the performance of the Vermilion Power Station Mercury Control Project. The project will result in the installation of a baghouse, along with a sorbent injection system, to control mercury emissions from Vermilion Units 1 and 2, with a goal of achieving 90% mercury reduction. For purposes of the Consent Decree, of the approximately $26.0 million expected capital cost for construction and installation of the baghouse with a sorbent injection system, DMG shall be deemed to have expended $7.5 million Project Dollars upon commencement of operation of this control technology, provided that DMG continues to operate the control technology for five (5) years and surrenders any mercury allowances and/or mercury reduction credits, as applicable, during the five (5) year period. DMG shall complete

construction and installation of the baghouse with a sorbent injection system, and commence operation of such control device, no later than June 30, 2007.

B. The proposed plan shall satisfy the following criteria:

1. Describe how the work or project to be performed is consistent with requirements of Section IV. A., above.
2. Include a general schedule and budget for completion of the construction of the baghouse and sorbent injection system, along with a plan for the submittal of periodic reports to the Plaintiffs on the progress of the work through completion of the construction and the commencement of operation of the baghouse and sorbent injection system.
3. The sorbent injection system shall be designed to inject sufficient amounts of sorbent to collect (and remove) mercury emissions from the coal-fired boilers and to promote the goal of achieving a total mercury reduction of 90%.
4. DMG shall not be permitted to benefit, under any federal or state mercury cap and trade program, from the operation of this project before June 30, 2012 (if such a cap and trade system is legally in effect at that time). Specifically, DMG shall not be permitted to sell, or use within its system, any mercury allowances and/or mercury reduction credits earned through resulting mercury reductions under any Mercury MACT rule or other state or federal mercury credit/allowance trading program, through June 30, 2012.
5. From July 1, 2007 through June 30, 2012, DMG shall surrender to EPA any and all mercury credits/allowances obtained through mercury reductions resulting from this project.
6. DMG shall provide the Plaintiffs, upon completion of the construction and continuing for five (5) years thereafter, with semi-annual updates documenting: a) the mercury reduction achieved, including summaries of all mercury testing and any available continuous emissions monitoring data; and b) any mercury allowances and/or mercury reduction credits earned through resulting mercury reductions under any Mercury MACT rule or other state or federal mercury credit/allowance trading program, and surrender thereof. DMG also shall make such semi-annual updates concerning the performance of the project available to the public. Such information disclosure shall include, but not be limited to, release of semi-annual progress reports clearly identifying demonstrated removal efficiencies of mercury, sorbent injection rates, and cost effectiveness.
7. Describe generally the expected environmental benefit for the project.

C. Performance - Upon approval of plan by the Plaintiffs, DMG shall complete the mitigation project according to the approved plan and schedule.

V. Municipal and Educational Building Energy Conservation & Energy Efficiency Projects

A. Within one hundred thirty five (135) days after entry of the Consent Decree, DMG shall submit a plan to Plaintiffs for review and approval for the completion of the Municipal and Educational Building Energy Conservation & Energy Efficiency Projects, as described herein. DMG shall spend no less than $1.0 million Project Dollars for the purchase and installation of environmentally beneficial energy technologies for municipal and public educational buildings in the Metro East area or the City of St. Louis.

B. The proposed plan shall satisfy the following criteria:

1. Describe how the work or project to be performed is consistent with requirements of Section V. A., above.
2. Include a general schedule and budget (for $1.0 million) for completion of the projects.
3. Describe generally the expected environmental benefit for the project.

C. Performance - Upon approval of plan by the Plaintiffs, DMG shall complete the mitigation project according to the approved plan and schedule, but no later than December 31, 2007.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 4
ATLANTA FEDERAL CENTER
61 FORSYTH STREET
ATLANTA, GEORGIA 30303-8960

February 26, 2002

4APT-APB

John S. Lyons, Director
Department for Environmental Protection
KY Natural Resources & Environmental
Protection Cabinet
803 Schenkel Lane
Frankfort, Kentucky 40601

Dear Mr. Lyons:

Thank you for sending the preliminary determination/statement of basis, draft prevention of significant deterioration (PSD) and title V draft permit received on January 8, 2001, for the Thoroughbred Generating Company, LLC project (Thoroughbred) located in Muhlenberg County, Kentucky. The preliminary determination is for the proposed construction and operation of a mine-mouth coal power plant project consisting of two (2) pulverized coal-fired steam generating units with a nominal generating capacity of 750 megawatts (MW) each and supporting emissions units. Potential emissions from the proposed project are above the thresholds requiring PSD review for nitrogen oxides (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), volatile organic compounds (VOCs), particulate matter (PM/PM_{10}), sulfuric acid mist (SAM), mercury and various other regulated pollutants.

Based on our review of the permit application, the preliminary determination, and PSD / title V permit, we have developed comments provided in the enclosure to this letter. When reviewing these comments, please note the following:

- In our comments we refer to the proposed project as the Thoroughbred Generating Station. Although we recognize that recent correspondence from the applicant contains the name Thoroughbred Energy Campus, we elected to use the Thoroughbred Generating Station name for consistency with the terminology in the draft permit.

- In our comments we refer to the "permit application." By use of this term, we mean the revised permit application dated October 26, 2001, and subsequent information provided by the applicant in response to questions raised by EPA Region 4 and other entities. Subsequent information includes the letter from Peabody Energy dated December 12, 2001.

- Although Peabody Energy submitted an original application for the project in February 2001, the project details and final evaluations on which the draft permit (issued in early January 2002) was based were not provided until very late November 2001 and mid-December 2001. (In fact some impact analysis evaluations had not been completed even as of the time the draft permit was issued.) Considering that the proposed project represents one of the largest emission sources proposed in all of Region 4 in many years, we are concerned that adequate time was not allowed to review the latest project information prior to draft permit issuance.

- At a time when cleaner coal technologies are emerging and other types of electric power generating technologies with lower emissions are available, Peabody has proposed an older pulverized coal design that will be installed at a facility that could be in operation for 50 years or more. Furthermore, the location of the Thoroughbred site in the middle eastern part of the United States is such that emissions from the facility could have effects within a wide area, including locations with existing air quality concerns. Therefore, in recognition of the older technology aspects, longevity and potential long-range effects of the proposed project, it is incumbent on the permitting authority to require the best possible controls (and control levels) and state-of-the-art emissions monitoring methods.

With proposed allowable emissions of nitrogen oxides equal to approximately 6,000 tons per year and proposed allowable emissions of sulfur dioxide equal to approximately 11,000 tons per year (not to mention substantial allowable emissions of other pollutants), the proposed project is of great importance to us. Therefore, we urge you to give careful attention to our comments during the remainder of the permitting process.

Thank you for the opportunity to comment on the Thoroughbred Generating Company, LLC project preliminary determination, draft PSD and title V permit. If you have any questions regarding these comments, please direct them to Jim Little at (404) 562- 9118, César Zapata at (404) 562-9139 or Stan Krivo at (404) 562-9123.

Sincerely,

/s/

Kay T. Prince
Chief
Air Planning Branch

Enclosure

U.S. ENVIRONMENTAL PROTECTION AGENCY
REGION 4, AIR PERMITS SECTION

Comments on Thoroughbred Generating Station Permit Application, Prevention of Significant Deterioration (PSD) Preliminary Determination/Statement of Basis and Draft PSD/Title V Operating Permit

5. PRELIMINARY DETERMINATION AND STATEMENT OF BASIS

6. Permit Application Summary Form

The first paragraph in the Source Process Description section includes a statement that the coal-fired steam generating units will operate in a combined cycle mode. This project does not include emissions units that would operate in a combined cycle mode. This same sentence refers to eight pulverized coal steam generating units at the facility, when in fact there will be two. Please revise this statement in the summary form.

7. Executive Summary

The last sentence of the second paragraph in the executive summary mentions that the PSD review involves six requirements. However, following that statement there is a list of seven requirements. Please, change the sentence so it will agree with the list in number.

8. Background

a. This paragraph includes a statement that the permit application for this project was logged complete on April 23, 2001. At this time, Region 4 still considers the application to be incomplete. The application does not include a Compliance Assurance Monitoring (CAM) plan as required in 40 C.F.R. § 64.4 and a complete Maximum Achievable Control Technology (MACT) case-by-case determination application as required in 40 C.F.R. § 63.43. Furthermore, to this date Thoroughbred has not submitted a complete CAM plan or a complete MACT case-by-case determination application. This section should be modified to reflect that the application is incomplete.

b. The statement "Information from the application is given and assumed" should be clarified or deleted, as it is not clear what it means.

9. Emissions Analysis Section and BACT Section D. Auxiliary Boiler

These sections state that the diesel-fired auxiliary boiler will operate 4,000 hours per year. However, this boiler is restricted to operate less 500 hours per year based on the air

quality analyses and as requested by Thoroughbred. Please replace the 4,000 hours per year with 500 hours per year.

10. Regulatory Review

a. Deficient Case-by-Case MACT Determination

The case-by-case MACT determination application submitted by Thoroughbred is deficient despite the fact that we have twice before asked that Thoroughbred submit a complete case-by-case MACT application in accordance with 40 C.F.R. § 63.43(e). To clarify any misunderstandings of what a complete case-by-case MACT determination application entails, the following is a list of the requirements found in 40 C.F.R. § 63.43(e) for a case-by-case MACT determination application.

i. An application for a case-by-case MACT determination (which includes a permit application under title V of the Act) shall specify a control technology selected by the owner or operator that, if properly operated and maintained, will meet the MACT emission limitation or standard as determined according to the principles set forth in paragraph 40 C.F.R. § 63.43(d).
ii. The name and address (physical location) of the major source to be constructed or reconstructed;
iii. A brief description of the major source to be constructed or reconstructed and identification of any listed source category or categories in which it is included;
iv. The expected commencement date for the construction or reconstruction of the major source;
v. The expected completion date for construction or reconstruction of the major source;
vi. The anticipated date of startup for the constructed or reconstructed major source;
vii. The hazardous air pollutants (HAP) emitted by the constructed or reconstructed major source, and the estimated emission rate for each such HAP, to the extent this information is needed by the permitting authority to determine MACT;
viii. Any federally enforceable emission limitations applicable to the constructed or reconstructed major source;
ix. The maximum and expected utilization of capacity of the constructed or reconstructed major source, and the associated uncontrolled emission rates for that source, to the extent this information is needed by the permitting authority to determine MACT;
x. The controlled emissions for the constructed or reconstructed major source in tons per year at expected and maximum utilization of capacity, to the extent this information is needed by the permitting authority to determine MACT;
xi. A recommended emission limitation for the constructed or reconstructed major source consistent with the principles set forth in 40 C.F.R. § 63.43(d) of this section;

xii. The selected control technology to meet the recommended MACT emission limitation, including technical information on the design, operation, size, estimated control efficiency of the control technology (and the manufacturer's name, address, telephone number, and relevant specifications and drawings, if requested by the permitting authority);
xiii. Supporting documentation including identification of alternative control technologies considered by the applicant to meet the emission limitation, and analysis of cost and non-air quality health environmental impacts or energy requirements for the selected control technology; and
xiv. Any other relevant information required pursuant to 40 C.F.R. § 63 subpart A.

Additionally, to further clarify the principles of MACT determinations, we are including the language found in 40 C.F.R. § 63.43(d). The following general principles shall govern preparation by the owner or operator of each permit application or other application requiring a case-by-case MACT determination concerning construction or reconstruction of a major source, and all subsequent review of and actions taken concerning such an application by the permitting authority:

i. The MACT emission limitation or MACT requirements recommended by the applicant and approved by the permitting authority shall not be less stringent than the emission control which is achieved in practice by the best controlled similar source, as determined by the permitting authority.
ii. Based upon available information, as defined in 40 C.F.R. § 63.42, the MACT emission limitation and control technology (including any requirements under paragraph 40 C.F.R. § 63.43(d)(3)) recommended by the applicant and approved by the permitting authority shall achieve the maximum degree of reduction in emissions of HAP which can be achieved by utilizing those control technologies that can be identified from the available information, taking into consideration the costs of achieving such emission reduction and any non-air quality health and environmental impacts and energy requirements associated with the emission reduction.
iii. The applicant may recommend a specific design, equipment, work practice, or operational standard, or a combination thereof, and the permitting authority may approve such a standard if the permitting authority specifically determines that it is not feasible to prescribe or enforce an emission limitation under the criteria set forth in section 112(h)(2) of the Act.
iv. If the Administrator has either proposed a relevant emission standard pursuant to section 112(d) or section 112(h) of the Act or adopted a presumptive MACT determination for the source category which includes the constructed or reconstructed major source, then the MACT requirements applied to the constructed or reconstructed major source shall have considered those MACT

emission limitations and requirements of the proposed standard or presumptive MACT determination.

For purposes of identifying control technologies options, available information means information contained in the following information sources as of the date of approval of the MACT determination by the permitting authority:

i. A relevant proposed regulation, including all supporting information;
ii. Background information documents for a draft or proposed regulation;
iii. Data and information available from the Control Technology Center developed pursuant to section 113 of the Act;
iv. Data and information contained in the Aerometric Informational Retrieval System including information in the MACT data base;
v. Any additional information that can be expeditiously provided by the Administrator; and
vi. For the purpose of determinations by the permitting authority, any additional information provided by the applicant or others, and any additional information considered available by the permitting authority.

According to section 112(g) requirements, Thoroughbred must provide a case-by-case determination application that meets the regulatory requirements outlined above. The document entitled "Case-by-Case MACT Determination" provided by Thoroughbred does not contain a complete case-by-case MACT determination application.

Although mercury is the HAP that is currently of most interest for coal-fired power plant MACT evaluations, other HAP will also be emitted from the Thoroughbred Generating Station's pulverized coal boilers. Based on emission estimates provided by the applicant, the following HAP must be considered in the case-by-case MACT evaluation: mercury, hydrogen chloride, hydrogen fluoride, metallic compounds (represented by arsenic, beryllium, chromium and manganese) and volatile organic HAP (represented by acetaldehyde, benzyl chloride, isophorone, methyl chloride, methyl ethyl ketone and propionaldehyde).

b. Missing Compliance Assurance Monitoring (CAM) Submittal

The information submitted by Thoroughbred does not meet the CAM rule requirements. 40 C.F.R. § 64.5(a) requires the owner or operator to submit to the permitting authority a monitoring plan that satisfies the design requirements in 40 C.F.R. § 64.3 as part of the application for an initial title V permit for "large" pollutant specific emissions units (i.e., emissions units with potential to emit a regulated air pollutant in an amount equal to or greater than the title V major source threshold). As stated in previous correspondence, the CAM submittal must be submitted for particulate matter (PM), particulate matter less than 10 micrometers in

diameter (PM_{10}), sulfur dioxide (SO_2), and nitrogen oxides (NO_x) in accordance with 40 C.F.R. §§ 64.3 and 64.4. At this time we consider the title V permit application incomplete

and technically deficient because of Thoroughbred's failure to include a CAM submittal with the application.

c. Missing Credible Evidence Language

The credible evidence language is not included in the preliminary determination and statement of basis. Please add the credible evidence language used in previous title V permits issued by KDAQ.

7. Additional Information Required in a Statement of Basis

The statement of basis (SB) must include a discussion of decision-making that went into the development of the title V permit to provide the permitting authority, the public, and the U.S. Environmental Protection Agency (EPA) a record of the applicability and technical issues surrounding issuance of the permit. A SB generally should include, but not be limited to, a description of the facility to be permitted, a discussion of any operational flexibility that will be utilized, the basis for applying a permit shield, any regulatory applicability determinations, and the rationale for the monitoring methods selected. A SB should specifically reference all supporting materials relied upon, including the applicable statutory or regulatory provision.

The SB could be revised to meet the intent of part 70 by containing a discussion on the monitoring and operational restriction provisions that are included for each emissions unit. 40 C.F.R. §70.6(a) requires that monitoring and operational requirements and limitations be included in the permit to assure compliance with all applicable requirements at the time of permit issuance. The selection of the specific monitoring procedures, including parametric monitoring and recordkeeping, and operational requirements must be explained in the SB.

The EPA Administrator's decision in response to the Fort James Camas Mill title V petition further supports this position. The decision is available on the Internet at www.epa.gov/region07/programs/artd/air/title5/petitiondb/petitions/fort_james_decision1999.pdf. The Administrator stated that the rationale for the selected monitoring method must be clear and documented in the permit record.

The SB must include a discussion of streamlining determinations. When applicable requirements overlap or conflict, the permitting authority may choose to include in the permit the requirement that is determined to be most stringent or protective as detailed in EPA's "White Paper Number 2 for Improved Implementation of the Part 70 Operating Permits Program" (March 5, 1996). The SB must explain why KDAQ concluded that

compliance with the streamlined permit condition assures compliance with all the overlapping requirements.

B. BEST AVAILABLE CONTROL TECHNOLOGY

1. Information Sources

As expressed in previous correspondence, we are concerned about the paucity of information sources referenced in assessing whether the control levels proposed are consistent with the levels that have been achieved elsewhere. The only reference source cited in the application is the RACT/BACT/LAER Clearinghouse (RBLC) database. As we have stated before, the RBLC is a starting point, not an ending point. And even when referencing the RBLC, the applicant excluded many entries as not applicable to the proposed project. For example, several RACT entries were excluded even though RACT and LAER examples are just as eligible for new BACT assessments as past BACT determinations. Also, units as large as 181 MW in the RBLC were excluded because they were only "a fraction" of the size of the proposed Thoroughbred units.

Further related to information sources, we note that Peabody Energy is considered the world's largest coal company. We would expect from this position that Peabody would have access to a wealth of information about coal-burning power plants that goes well beyond the information available in the RBLC. Given Peabody's prominence in the world coal market, we would further expect Peabody to have information on coal-fired power plants outside the United States. Employed technologies and achieved emission rates outside the U.S. are definitely eligible for consideration in a BACT evaluation.

As examples of the types of information and reference sources that could have been consulted and that we believe should be consulted before issuance of a final permit, we list the following:

a. The nitrogen oxides (NO_x) control levels achieved (or expected to be achieved) at the many existing coal-fired power plants that have installed (or are planning to install) selective catalytic reduction (SCR) controls for NO_x SIP call purposes or other purposes.

b. The sulfur dioxide control levels achieved (or expected to be achieved) at the existing coal-fired power plants that have installed (or are planning to install) flue gas desulfurization (FGD) equipment for acid rain regulatory purposes (or other purposes). For example, Tennessee Valley Authority (TVA) has installed FGD equipment and has announced plans to install additional equipment.

c. Technical articles such as the following:

- R.K. Srivastava and W. Jozewicz, 2001, Flue Gas Desulfurization: The State of the Art, *Journal of the Air & Waste Management Association*, Vol. 51, p. 1676-

1688.

- R.K. Srivastava, C.B. Sedman and J.D. Kilgore, 2001, Preliminary Estimates of Performance and Cost of Mercury Control Technology Applications on Electric

- Utility Boilers, *Journal of the Air & Waste Management Association*, Vol. 51, p. 1460-1470.

d. The control methods and emission rates proposed by Peabody Energy for the Prairie State Energy Campus project in Illinois. (The Prairie State project is essentially identical to the Thoroughbred Generating Station project.)

e. Information available in tables on EPA's Clean Air Market Programs website (at www.epa.gov/airmarket/emissions/).

f. Various proprietary databases. An example is the international database developed by IEA Coal Research - The Clean Coal Centre. The latest version of this database is named CoalPower4 and contains information for installations around the world. General information for the IEA Coal Research - Clean Coal Centre can be found at the following Internet website: www.iea-coal.org.uk/aboutiea/welcomeIEApage.htm.

g. Permits, permit applications or other information for the pulverized coal boiler projects listed below that we understand are under development or are planned for development. (Some of these projects are at new sites, others at existing facilities.) Note that this list is meant to be illustrative and not inclusive of all new projects in the United States. Furthermore, it does not include any projects in other countries or retrofits of existing pulverized coal boilers (see separate list below).

- Cornbelt Energy, Prairie Energy Power Plant (Illinois)
- Dynegy - Illinois Power, Baldwin Plant (Illinois)
- Midwest Generation, Morris Plant (Illinois)
- Kansas City Power & Light, Hawthorn Power Station (Missouri)
- Plum Point Energy (Arkansas)
- Unisource Energy and Salt River Project, Springerville Station (owned by Tucson Electric) (Arizona)
- Santee Cooper, Cross Generating Station (South Carolina)
- Kansas City Power & Light (Great Plains Power), Weston Bend I Station (Missouri)
- Sunflower Electric Power, Holcomb Power Plant (Kansas)
- Bull Mountain Development, Roundup Power Project (Montana)
- Rocky Mountain Power, Hardin Generator Project (Montana)

In summary, using the RBLC exclusively, the applicant cites only five projects as comparable for comparison with the proposed Thoroughbred Generating Station. We believe that this falls far short of being an adequate comparison.

2. Coal Washing

To satisfy comments made by EPA, the applicant has provided an analysis on coal washing as a possible addition to BACT requirements for SO_2 emissions. We have the following additional comments on coal washing:

a. Peabody Energy has proposed a project to be located in Illinois that is essentially identical to the Thoroughbred project. The Illinois project is referred to as the Prairie State Energy Campus. We are interested to know if coal washing will or will not be used in connection with the Prairie State project.

b. Not having received any information about the mine that will supply coal to the Thoroughbred Generating Station, we can only assume that the capacity of the mine is great enough to provide coal for uses other than as a source of coal for Thoroughbred. If this is the case, we recommend that a permit condition be added that would require the owner/operator of the Thoroughbred Generating Station to use washed coal if a coal washing operation is installed at the mine for supply of coal to other customers.

c. The applicant's analysis of coal washing points out the potential adverse environmental effects resulting from solid and liquid wastes produced by coal washing. While this observation is valid, we note for your attention that coal washing is commonly practiced at many mines and that the generation of waste materials does not mean necessarily that coal washing should be eliminated from further consideration.

d. The cost data provided for coal washing appears to concentrate on the incremental cost of controlling SO_2 emissions by washing coal. For a complete evaluation of the coal washing option, we recommend that KDAQ obtain or develop an estimate of total cost effectiveness (annualized dollars per ton removed) for coal washing plus FGD. Although the incremental cost effectiveness may be high, the total cost effectiveness may be reasonable.

e. Coal washing may have beneficial air emissions effects in addition to removal of sulfur. The inert solids retained in the washing waste material may help reduce boiler emissions of particulate matter and hazardous air pollutant trace elements such as mercury.

3. Alternative Designs and Fuels

We are aware of comments that have been made recommending consideration of alternative designs and alternative fuels. The alternative designs that have been mentioned are circulating fluidized bed boilers and integrated gasification combined cycle combustion turbines. The alternative fuels that have been mentioned include low sulfur coals that are used widely in the eastern United States. As the permitting authority, it is in your discretion to require a detailed evaluation of such alternatives as part of the BACT evaluation. Regardless of whether you elect to require a detailed evaluation before reaching a final BACT determination, we recommend that you include documentation from the applicant in your files providing a rationale as to why a configuration of pulverized coal boilers burning high-sulfur western Kentucky coal was selected for this project and why other design and fuel alternatives were eliminated.

4. Compliance Averaging Period for Pulverized Coal Boiler Emissions

In KDAQ's draft permit, the compliance averaging period is 30 days for emissions of sulfur dioxide, nitrogen oxides and carbon dioxide. If a 30-day averaging period is adopted in the final permit, this lengthy period can accommodate short-term fluctuations above the limits so long as the average emissions rates over 30 days are in compliance. In developing the final BACT emissions limits, therefore, KDAQ should take into account the compliance averaging period. For example, a NO_x emissions limit of less than the proposed limit could well be achievable on a 30-day average basis (see below).

5. BACT for Pulverized Coal Boiler Nitrogen Oxides Emissions

The control method proposed as BACT for NO_x emissions from the pulverized coal boilers is a combination of low NO_x burners and selective catalytic reduction (SCR). We agree that this combination represents the type of control representative of BACT. Our concern is with the emissions level proposed as BACT in the draft permit, namely, 0.09 lb/MMBtu heat input on a 30-day rolling average basis. Stated in terms of SCR control efficiency, this emissions level appears to represent a 67-percent removal of NO_x emissions produced by the low NO_x burners. In theory, SCR can produce a much higher NO_x control efficiency than 67 percent when used with coal-fired boilers. A possible explanation for the lower efficiency may be that the low concentration of NO_x when firing with low NO_x burners does not lend itself to high SCR control efficiency. So far as we know, the applicant has not provided its own explanation of the low efficiency or offered an SCR vendor's statement that a higher efficiency is not achievable for this specific project. Furthermore, so far as we know, the applicant has not provided details about either the low NO_x burner configuration or the SCR system to demonstrate that the control level proposed can be achieved and that any corollary environmental impacts will be minimized. For example, the applicant has not provided a discussion of the ammonia injection design and the number and surface area of catalyst layers that will help achieve low NO_x emissions and low ammonia slip.

In addition, as discussed above, since KDAQ has proposed that the NO_x BACT emissions limit be met on a 30-day average (if this compliance averaging period is retained in the final permit), consideration of a lower emissions limit is appropriate given that a 30-day period would tend to smooth out any peaks in emissions.

Further, we are aware of the following existing pulverized coal power plants where we understand SCR systems have been installed. We list these facilities to indicate that information is available beyond what is presented in the permit application. This list is illustrative and not inclusive of all SCR retrofits.

- Georgia Power, Plant Bowen (Georgia)
- Wisconsin Electric - Wisconsin Gas, Pleasant Prairie Plant (Wisconsin)
- American Electric Power, Gavin Plant (Ohio)
- American Electric Power, Cardinal Plant (Ohio)
- American Electric Power, John Amos Plant (West Virginia)
- American Electric Power, Mountaineer Plant (West Virginia)
- Vectren Power Supply, Culley Station (Indiana)
- Vectren Power Supply, A.B. Brown Station (Indiana)
- Southern Illinois Power Cooperative, Marion Power Station (Illinois)
- Tennessee Valley Authority, Paradise Plant (Kentucky)
- AES, Somerset Plant (New York)

In summary, KDAQ should consider other information sources and should evaluate the feasibility of a lower NO_x emissions limit for the pulverized coal boilers before issuing a final BACT determination.

6. <u>BACT for Pulverized Coal Boiler Sulfur Dioxide Emissions</u>

The primary control method proposed as BACT for SO_2 emissions from the pulverized coal boilers is use of wet limestone scrubbers. Although this control approach is generally representative of BACT for SO_2 emissions, the applicant has not provided details on the design of the wet scrubbers to demonstrate that the control level proposed can be achieved. For example, the applicant has not presented information on the exact scrubber design intended (forced oxidation or other, etc.), the scrubber models being considered and the expected vendor guarantees for these models, and any supplemental control enhancements (such as use of organic acid additives) that will or will not be used. In addition, since the proposed BACT emissions limit of 0.167 lb/MMBtu is apparently based on a worst-case coal but is to be met on a 30-day average (if this compliance averaging period is retained in the final permit), consideration of a lower emissions limit is appropriate given that a 30-day period would tend to smooth out peaks in emissions resulting from occasional use of worst-case coal. Please also note our previous comments on coal washing to reduce sulfur compound emissions.

7. <u>BACT for Material Handling Equipment</u>

The BACT evaluation in the revised permit application contains a statement that baghouses and bin vent filters were chosen as BACT for material handling facilities for coal, FGD reagent, and ash. However, the BACT portion of the application does not list the specific emissions units covered by this statement and does not identify BACT emissions levels, grain loadings, or control efficiencies achievable by the use of the selected control methods. In addition, there is no BACT study that supports the selection of these control technologies for these emissions units. The permit also does not include any BACT requirements for these emissions units. These units are subject to BACT and the permit must include the BACT emission limitations, efficiencies, etc.

8. BACT for Fugitive Particulate Matter Emissions

KDAQ's preliminary determination does not address BACT for fugitive particulate matter emissions. Potential sources of fugitive particulate matter emissions include material storage areas (coal, limestone, ash), conveyors and roadways.

The applicant's response to our previous comment about the lack of a BACT assessment for fugitive particulate matter emissions is embodied in the following statement: "Therefore, Thoroughbred proposes the use of enclosures, low drop heights, compaction, and suppression aids as practical to control fugitive emissions and prevent opacity exceedences from all PM fugitive sources." The applicant did not identify the potential fugitive-emitting equipment and/or activities that will be enclosed or the type of enclosure; did not identify the potential fugitive-emitting equipment and/or activities that will be controlled by low drop heights; did not identify the potential fugitive-emitting equipment and/or activities that will be controlled by compaction or the frequency and method of compaction; and did not identify the potential fugitive-emitting equipment and/or activities that will be controlled by suppression or the type and frequency of suppression applications.

9. "Beyond BACT" Comments

KDAQ's preliminary determination and certain comments from the applicant include use of the term "beyond BACT." We discourage the use of this term in further documentation for this project. If KDAQ determines that a given control method and emissions level is achievable and acceptable from the standpoint of economics, environmental effects and energy use, then this is a BACT determination and not a "beyond BACT" determination. The emissions limits and control requirements in the final permit will be eligible for consideration as BACT for any similar future project.

10. BACT for Pulverized Coal Boiler Startup and Shutdown Emissions

In the draft permit, KDAQ exempts the facility owner/operator from compliance with the emissions limits for the pulverized coal boilers during periods of startup and shutdown. Since startup and shutdown are part of normal operation, however, emissions during these periods are subject to BACT requirements. KDAQ should specify the requirements to minimize emissions from the pulverized coal boilers during startup and shutdown. These requirements could include a limitation on the number of boiler firing hours without pollution control devices (SCR, baghouse, FGD scrubber, wet ESP) in operation and (if feasible) a requirement to fire liquid or gaseous fuels only until pollution control devices are operating.

3. AIR QUALITY IMPACT ANALYSIS

The air quality impact assessment provided in both the PSD permit application and the preliminary determination has not addressed a number of previously provided review comments. Until the issues upon which the comments were based are resolved, we believe the preliminary determination air quality assessment contains incomplete, and/or inaccurate information. Thus the air quality information provided for public review may not be sufficient for their evaluation. The following are the air quality issues that remain unresolved:

4. <u>Ambient Impact Assessment for "Significant" Pollutants</u>

The permit application includes an ambient impact analysis for NO_x, SO_2, CO, and PM/PM_{10} because estimated emissions of these pollutants exceed the listed PSD significant emissions rates in 401 KAR 51:017, Section 22. Estimated emissions of VOC (surrogate for ozone), sulfuric acid mist, mercury, and fluorides also exceed the listed significant emissions rates. Therefore, an ambient air quality impact analysis for these pollutants should be provided. Furthermore, as discussed below, Kentucky PSD rules as currently written include as significant any emissions of a pollutant regulated under the Clean Air Act that does not have a defined significant emissions rate threshold. As a consequence, several other pollutants are also potentially subject to PSD review.

5. <u>Worst-case Operating Scenarios</u>

The preliminary determination indicates impact assessments were performed for 100%, 75% and 50% operational loads. Although 100% load was selected as the worst-case operation scenario, the basis for this determination has not been provided (e.g., the emission values and exit stack parameters modeled for each combination of load and seasonal ambient temperatures).

6. <u>Other Emission Sources</u>

The following are comments provided on the inventories of other national ambient air

quality standards (NAAQS) and PSD emission sources:

a. In response to our comment on the inventory of PM_{10} emission sources considered in the impact assessment, a list of PM_{10} sources was provided (Peabody Energy letter of December 13, 2001 to KDAQ). We assume that this list contains all PM_{10} emission sources identified within 50 km of the PM_{10} significant impact area (i.e., area of 2.5 km radius about Thoroughbred). The following comments are associated with this listing:

   · The distance (D) in the 20D procedure used to eliminate emission sources from the modeling analysis was measured from Thoroughbred to the source of interest. This is correct when addressing the 24-hour standards but not for the annual. The correct D value for the annual impact assessments is measured from the outer boundary of the significant impact area (SIA) to the source of interest.

   · The emission values for each source provided in the listing do not agree with the values used in the modeling. The listed emissions are much larger that those used in the modeling.

   · The rationale for the elimination of emission sources does not appear to be consistently applied. A source (Dart Container Corp.) with less than the 20D emission rate at a location greater than 50 km from Thoroughbred was not eliminated from the modeling, while a larger emission source (Midwestern Gas Transmission) with an emission rate less than the 20D value located about 30 km away was eliminated.

b. Peabody Energy has indicated (letter of December 13, 2001, to KDAQ) that all missing or incorrect emission inventory information was verified by contacting the source or regulatory agency, and that provided exit velocities were reviewed for accuracy. However, Peabody Energy did not identify which entries were substitute values for missing or incorrect data. In addition, the emission inventories still contain exit stack velocities that exceed reasonable levels (e.g., in excess of 200 fps).

c. Proper PSD increment consumption analyses for both PM_{10} and SO_2 have not been provided. Although the application indicates Thoroughbred will set the minor source baseline date for Muhlenberg County, this does not necessarily mean that all PM_{10} or SO_2 emission sources identified in Tables 6.3.1-7 and 6.3.1-8 are non-PSD sources. Because the emission sources and modeled receptors are located outside Muhlenberg County, some of the emission sources could be PSD increment consuming based on other applicable minor source baseline dates. Confirmation is needed that no PSD increment consuming source exists for the receptors modeled.

d. The PSD Class I emission inventory only included sources within 100 km of Mammoth Cave. In telephone discussions on this issue, both EPA and the National

Park Service (NPS) indicated the need to include large emission sources beyond this distance (e.g., up to 200 km) that could significantly impact Mammoth Cave. EPA and NPS volunteered to assist Peabody Energy's environmental consultant in identifying these large emission sources. The Class I impact analysis is not complete without inclusion of applicable large emission sources beyond 100 km.

4. Thoroughbred Emission Sources

The following comment is associated with the modeled Thoroughbred emission sources. The Auxiliary Boiler, Emergency Diesel Generator, Coal Reclaim Hoppers, Secondary Stacker, and Secondary Stock Pile were modeled with zero hours of operation. Peabody indicates the auxiliary boiler is a backup unit that will not operate when the coal-fired boilers are operating. The emergency generator will only operate during emergencies or testing, and the coal reclaim hoppers, secondary stacker, and secondary stock pile will only operate in emergency situations when the primary units are down. The permit should contain operational restrictions for these units. Permitted operation for up to 500 hours per year is not appropriate without impact consideration.

5. Background Concentrations

The PM_{10} background concentrations were obtained from monitors at Henderson and Owensboro, Kentucky from a 1998 report. Peabody has indicated that these are the nearest PM_{10} monitors to Thoroughbred and that KDAQ has accepted them as representative of Muhlenberg County. More recent measurements from these monitors should be provided as well as the reason for the selection of 1998.

6. Determination of Maximum Concentrations

Only the maximum annual and high second-highest coarse grid concentrations were included in the refined modeling. To properly determine SIA, PSD increment consumption and NAAQS compliance, all maximum concentrations and concentrations challenging these values (e.g., concentrations within 10 percent of these maximums), for each combination of pollutant/averaging period, should be modeled to 100-m resolution. This is especially important given the coarseness of the initial receptor grids.

7. NAAQS Modeling Results

The proper NAAQS compliance assessment was not provided. The sum of the modeled cumulative concentrations for all sources (i.e., proposed Thoroughbred plus all other modeled emission sources) and the applicable representative monitored background concentration should be compared to the appropriate NAAQS. This was not the procedure used in the application or the preliminary determination.

8. Vegetation Impacts

The vegetation sensitivity levels used for impact comparison are ambient concentrations. These values were inappropriately compared with modeled incremental Thoroughbred concentrations. The cumulative ambient concentrations from all emission sources should be used for comparison with Table 7.5.3-1 vegetation sensitivity levels.

9. PSD Class I Area Assessment

Both the methodology used to assess visibility impacts in the Mammoth Cave PSD Class I area and the impacts provided in the application and preliminary determination should be reviewed and approved by the applicable Federal Land Manager (FLM). During conference telephone discussions on the Class I impact assessment, the FLM has identified modeling issues that must be resolved before the provided Class I area impact assessment can be accepted. In addition, the FLM has indicated that the calculated impacts using the questionable modeling procedure show Thoroughbred emissions producing visibility impacts at Mammoth Cave greater than the acceptable extintion values.

D. PERMIT TERMS AND CONDITIONS

1. Missing Regulatory Authority for Each Term and Condition in Permit

40 C.F.R. § 70.6(a)(1)(i) requires that the permit specify and reference the origin and authority for each term and condition. Please include the regulatory authority for each term and condition of the permit.

2. Description of Emissions Units 01 and 02

The descriptions of these emissions units include a reference to natural gas to be used for startup and stabilization. Based on the BACT study submitted by Thoroughbred, natural gas will not be available at the site. Please delete the reference to natural gas in the descriptions of the emissions units. If natural gas will be available in the future, then any BACT determinations that were deemed infeasible because of lack of natural gas availability must be redone.

3. Operational Limitations - BACT Requirement

The permit does not require the installation of control devices for any of the affected emissions units with control devices selected to meet BACT requirements. The permit must require the installation of the control devices selected as BACT. Additionally, the permit must specify monitoring to assure compliance with the BACT requirements pursuant to 40 C.F.R. § 70.6(a)(3)(i)(B) and 40 C.F.R. § 70.6(c)(1).

4. Section B.2. Emissions Limitations - Missing Applicable Requirements for Emissions

Unit 01 and 02

The source is subject to the requirements in 40 C.F.R. § 40.42a - 40.44a for particulate emissions, opacity, SO_2, CO and NO_x. When applicable requirements overlap or conflict, the permitting authority may choose to include in the permit the requirement that is determined to be most stringent or protective as detailed in EPA's "White Paper Number 2 for Improved Implementation of the Part 70 Operating Permits Program" (March 5, 1996). However, the citations for all applicable requirements must be included in the permit.

5. Section B.3. Testing for Emissions Units 01 and 02

a. The testing requirements in this section do not specify which pollutants Thoroughbred must test to demonstrate compliance. For practical enforceability, the permit must specify which pollutants need to be tested and what reference method should be used to demonstrate compliance.

b. Compliance must be assured for all regulated pollutants, including HAP. The frequency of the tests must be specified also. Specifically, for HAP, until a good correlation between the grab sample of the fuel and emissions is established, Thoroughbred should conduct compliance emissions tests periodically, for example, every six months or every year to demonstrate compliance.

6. Emissions Limitations - Averaging Times for All Emissions Units

The 30-day rolling average compliance times for SO_2 and CO are not adequate to ensure protection of all NAAQS and PSD increments. The NAAQS and PSD increments for SO_2 include ambient limits for averaging periods of 3 hours and 24 hours, and the NAAQS for CO are expressed in terms of 1-hour and 8-hour averaging periods. Therefore, compliance with the 30-day rolling average emission limits does not adequately demonstrate compliance with the short-term NAAQS or PSD increments. Consequently, to ensure protection of the NAAQS and PSD increments, enforceable short-term limits of 24 hours or less should be established in the permit for SO_2 and CO.

The permit does not contain any compliance averaging time for the other regulated pollutants (mercury, fluorides, etc.). Please include compliance average times for the other regulated pollutants and discuss how compliance with the emission limitations will be determined.

7. Qualitative Visual Observations to Assure Compliance with Opacity Limitations for All Emissions Units

The permit requires qualitative visual observations to assure compliance with opacity limitations for several emissions units. These qualitative visual observations require that

the opacity of emissions be determined by reference method 9 if the emissions from any stack during the qualitative visual observations are perceived or believed to exceed the applicable standard. This language is not practically enforceable as it leaves to interpretation what is perceived or believed to exceed the standard. Because the person performing the qualitative visual observation may not be a certified method 9 reader, it would be impossible for this person to determine if the emissions exceed the opacity standard. Consequently, the reference to perceived and believed must be replaced by language stating that if any visible emissions are seen, then the opacity must be determined using reference method 9.

8. Particulate Matter Monitoring for the Coal-fired Boilers, Emissions Units 01 and 02

The technologies for particulate matter (PM) continuous emission monitoring systems (CEMS) have become much better established, including technologies for emissions units with wet scrubbers. This is evidenced in part by the expectation that in the near future EPA will issue a final rule revision adding Performance Specification 11 (PS-11) to 40 C.F.R. part 60. PS-11 is entitled *Procedures for Particulate Matter Continuous Emission Monitoring Systems at Stationary Sources*. We therefore strongly recommend that KDAQ consider adding a PM CEMS requirement for the two pulverized coal boilers.

9. Carbon Monoxide Monitoring for the Coal-fired Boilers, Emissions Units 01 and 02

Pursuant to 40 C.F.R. § 70.6(a)(3)(i)(B) and 40 C.F.R. § 70.6(c)(1) the permit must contain monitoring sufficient to assure compliance with the applicable requirements. The permit does not specify any monitoring requirements for the carbon monoxide applicable requirements for the two pulverized coal boilers. We therefore strongly recommend that KDAQ consider adding a carbon monoxide CEMS requirement for the two pulverized coal boilers.

10. Emissions Limitations - Startup, Shutdown, or Malfunction Emissions Standards Exemptions for All Emissions Units

The permit exempts the emissions units from the emission standards during startup, shutdown or malfunction. This exemption is contrary to 401 KAR 50:055 Section 1. The emissions units must comply with the emission limits at all times. During periods of violations of the emission standards during startup, shutdown or malfunction, the permittee must follow the procedures in 401 KAR 50:055 Section 1. For all emissions

units which are exempted from emissions limitations during startup, shutdown or malfunctions, the permit must be revised to comply with 401 KAR 50:055 Section 1.

11. Compliance Assurance for All Emissions Units

Pursuant to 40 C.F.R. § 70.6(c)(1), we request that the statement of basis include a

section that explains how Thoroughbred will assure compliance with all applicable requirements for each emissions unit. This explanation must include the rationale for the selection of the monitoring requirements for each applicable requirement.

12. Section B.7.a. Specific Control Equipment Operating Conditions for Pulverized Coal Fired Boilers, Emissions Units 01 and 02

This condition requires Thoroughbred to operate the particulate control devices as necessary to maintain compliance with permitted emission limitations. This condition is vague and unenforceable. As required in 40 C.F.R. § 64.4, Thoroughbred must submit a CAM plan that would establish the control device parameters to record and ranges that will assure compliance with the applicable requirement. This condition must be replaced with the contents of the CAM plan for particulate emissions.

13. Section B.1. Operating Limitations for the Auxiliary Boiler, Emissions Unit 03

The language in this condition is unenforceable as written. Therefore, the restriction must read "the permittee shall not operate the auxiliary boiler more than 500 hours per 12 consecutive months."

14. Monitoring Requirements for the Auxiliary Boiler

The auxiliary boiler is restricted to 500 hours per 12 consecutive months. However, there is no monitoring requirement to assure compliance with this requirement. Pursuant to 40 C.F.R. § 70.6(a)(3)(i)(B) and 40 C.F.R. § 70.6(c)(1), the permit must include monitoring to assure compliance with this requirement.

15. Coal Handling Systems Emissions Units Applicable Requirements and Monitoring

a. The permit does not require the installation of control devices that were determined to be part of the BACT determination. The permit must require the installation of these control devices and include in the permit emissions rate limitations based on air quality modeling and BACT requirements. Additionally, the permit must specify monitoring to assure compliance with the BACT requirements pursuant to 40 C.F.R. § 70.6(a)(3)(i)(B) and 40 C.F.R. § 70.6(c)(1).

b. Regulation 401 KAR 63:010, Section 3 requires taking precautions to prevent fugitive particulate matter from becoming airborne. The permit must specify the precautions that Thoroughbred will use to minimize fugitive particulate matter emissions. Additionally, the permit must contain monitoring to assure compliance with this applicable requirement pursuant to 40 C.F.R. § 70.6(a)(3)(i)(B) and 40 C.F.R. § 70.6(c)(1).

16. Coal Handling System, Emissions Unit 05

It is our understanding that these emissions points are for emergency purposes only and were not modeled in the air quality analyses. There must be a condition in the permit that prohibits the use of these emissions units in conjunction with the other coal handling systems and that allows them to operate only during emergencies. The meaning of emergency for the purpose of this emissions unit should be defined in the permit.

17. Specific Control Equipment Operating Conditions for Coal Handling Systems, Emissions Units 04 and 05

The conditions in this section are vague and unenforceable. Thoroughbred must determine the parameters to record and ranges that will assure compliance with the applicable requirements. The permit must include operating conditions and monitoring that will assure compliance with the applicable requirements pursuant to 40 C.F.R. § 70.6(a)(3)(i)(B) and 40 C.F.R. § 70.6(c)(1).

18. Applicable Requirements for Emissions Unit 06 - Coal Piles, Emissions Unit 07 - FGD Reagent Prep Handling, Emissions Unit 08 - FGD Reagent Prep Handling (Fugitives), Emissions Unit 09 - Fly Ash Handling System

a. The permit does not specify what BACT is for these emissions units. The permit must include in the permit emissions rate limitations based on air quality modeling and BACT requirements. Additionally, the permit must specify monitoring to assure compliance with the BACT requirements pursuant to 40 C.F.R. § 70.6(a)(3)(i)(B) and 40 C.F.R. § 70.6(c)(1).

b. Regulation 401 KAR 63:010, Section 3 requires taking precautions to prevent fugitive particulate matter from becoming airborne. The permit must specify the precautions that Thoroughbred will use to minimize fugitive particulate matter emissions. Additionally, the permit must contain monitoring to assure compliance with this applicable requirement pursuant to 40 C.F.R. § 70.6(a)(3)(i)(B) and 40 C.F.R.
§ 70.6(c)(1).

19. Specific Control Equipment Operating Conditions for Emissions Unit 06 - Coal Piles, Emissions Unit 07 - FGD Reagent Prep Handling, Emissions Unit 09 - Fly Ash Handling System

The conditions in this section are vague and unenforceable. Thoroughbred must determine the parameters to record and ranges that will assure compliance with the applicable requirements. The permit must include operating conditions and monitoring that will assure compliance with the applicable requirements pursuant to 40 C.F.R. § 70.6(a)(3)(i)(B) and 40 C.F.R. § 70.6(c)(1).

20. Section D.2. and D.3. Performance Tests Requirements

These sections require performance tests for certain pollutants and emissions units. However, the sections do not specify when those tests must be performed. For practical enforceability purposes, these sections should include a time frame indicating when these tests should be conducted.

21. MACT General Provisions

a. The permit does not contain a startup, shutdown, and malfunction plan as required in 40 C.F.R. § 63.6(e)(3). If Thoroughbred believes that there are alternative startup, shutdown, and malfunction plans which are equivalent to the requirements in 40 C.F.R. § 63.6(e)(3), then that determination must be submitted as part of the case-by-case MACT determination application. The permit should include the startup, shutdown, and malfunction plan as required in 40 C.F.R. § 63.6(e)(3).

b. The permit should require Thoroughbred to comply with all section 112(g) requirements until the effective date of the promulgated MACT standard.

22. Inclusion of the Emissions Units from the Mine in the Permit

The permit does not contain the emissions units from the mine. There are no explanations in the SB or permit about the emissions units from the mine. The SB should include a description of the mine, its distance from the generating station, and an explanation as to whether the mine and the generating station should be considered one source for PSD and title V purposes. From the limited information submitted by Thoroughbred, it seems that the mine should be considered one source for PSD and title V purposes and the emissions units should be included in the permit. In addition, these mine emissions units would be subject to BACT. (See further discussion below on this subject)

23. Emergency Provisions, Section G - General Provisions

This section specifies ten (10) working days after emission limitations are exceeded as the deadline to submit a written notice of emergency. 40 C.F.R. § 70.6(g)(3)(iv) requires this notice to be submitted within two (2) working days after the emission limitations are exceeded for an emergency to constitute an affirmative defense to an action brought for noncompliance with technology-based emission limitations. Please change the emergency notice submittal deadline to two (2) working days after the emission limitations are exceeded, in accordance with 40 C.F.R. § 70.6(g)(3)(iv).

24. Prohibition of Default Issuance of Title V Permits

40 C.F.R. § 70.8(e) prohibits the issuance of a title V permit by default. Consequently, the proposed title V permit should not be signed and should not be allowed to become the

final title V permit automatically after EPA's comment period is over. While the state may issue a title V permit when EPA has not objected within 45 days of receipt of the proposed title V permit and all necessary supporting information, the permit review and issuance process is confounded whenever EPA requires additional supporting information or does object within 45 days.

25. Permit expiration language

In section G, general requirements, subsection b, the draft permit contains language that resembles title V expiration and permit renewal requirements. This permit is a PSD permit and its requirements do not expire. We recommend the following language: *Terms and conditions in this permit established pursuant to the construction authority of 401 KAR 51:017 or 401 KAR 51:052 shall not expire*.

E. EQUIPMENT DESCRIPTION

We remain concerned about the lack of details provided in the application for various types of equipment, especially the pulverized coal boilers and associated emissions control equipment. For example, the applicant not only does not identify the pulverized coal boiler manufacturer and model, no information is provided on the expected firing configuration of the pulverized coal boilers that will be installed. As an example previously given related to boiler emissions control equipment, the applicant commits to use of wet limestone flue gas desulfurization scrubbers but does not provide the scrubber manufacturer and model, the design details that would allow the permitting authority to evaluate whether the selected scrubber can achieve the control levels proposed, or even a statement as to the type of limestone scrubber. We are not convinced that a supportable permit can be issued without more detailed information.

F. SINGLE SOURCE DETERMINATION FOR MINE AND POWER PLANT

The proposed title V permit (which constitutes the final PSD permit) should not be issued until a determination is made regarding whether the power generating facility and the associated mine are a single source for PSD and title V permitting purposes. If a determination is made that they are a single source, the emissions units at the mine must undergo a BACT evaluation before a permit can be issued and the permit must include emissions units at the mine. Related to this issue, if KDAQ determines that the power generation facility and the mine are not a single source, we request written justification of this determination before a proposed title V (final PSD) permit is issued.

G. PSD REVIEW FOR "OTHER" REGULATED POLLUTANTS

In the preliminary determination and statement of basis, KDAQ has not explicitily addressed our previous comment concerning compliance with Kentucky requirements in

401 KAR 51:017, Section 1(37)(b). This rule defines a significant emissions rate for PSD review purposes as any emissions of a pollutant regulated under the Clear Air Act that is not listed in Section 22. (Section 22 lists significant emissions rates for 19 specific pollutants or categories of pollutants.) Under Kentucky rules, for example, emissions of hydrochloric acid (specified in the Clean Air Act as a regulated hazardous air pollutant) from combustion of coal in the pulverized coal boilers is subject to PSD review requirements including a BACT determination and an evaluation of ambient impacts. KDAQ either needs to provide a justification prior to issuance of a final PSD permit as to why this rule is not applicable to the Thoroughbred Generating Station project or a PSD review of the affected pollutants should be conducted prior to final PSD permit issuance. If KDAQ elects to conduct a PSD review, we can assist in identifying the pollutants that can be the focus of this review.

H. IMPACT OF MERCURY EMISSIONS

Mercury has been identified as a persistent bioaccumulative toxic chemical, primarily because of its ability to transform in the ambient environment to methylmercury that is often observed to concentrate in the food chain. Proposed emissions of mercury for the Thoroughbred project (420 pounds per year) exceed the PSD significant emissions rate threshold (200 pounds per year). However, neither the permit application nor KDAQ's preliminary determination and statement of basis contains an assessment (qualitative or quantitative) assessing whether the proposed mercury emissions pose a risk of adverse impact on the ambient environment.

I. EMISSION RATE ESTIMATES

The permit application includes emission factors (in Section 10 of Appendix A) on which emission estimates were based. In many cases, the basis for these emission factors does not appear. For example, the uncontrolled NO_x emissions rate for the pulverized coal boilers at 100% load is listed as 2011.6216 lb/hr (which is equivalent to about 0.27 lb/MMBtu). The applicant does not indicate if this emissions rate is based on vendor data, data for similar boilers or something else. As still another example, the permit application emissions estimation tables list boiler pollutants with a "†" footnote symbol, but no footnote is provided that is marked with this symbol. As another example, the permit application emission factor references for pulverized coal boiler hazardous air pollutant emissions include "Table 1.1-13," "Table 1.1-14" and "Table 1.1-18." However, the application does not list the reference containing these tables. We presume that the reference is EPA's AP-42 emission factors compilation, but we are not certain of this.

United States
Environmental Protection
Agency

Office of Air Quality
Planning and Standards
Research Triangle Park, NC 27711

EPA-454/R-98-019
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AIR

INTERAGENCY WORKGROUP ON AIR QUALITY MODELING (IWAQM) PHASE 2 SUMMARY REPORT AND RECOMMENDATIONS FOR MODELING LONG RANGE TRANSPORT IMPACTS

EPA-454/R-98-019

INTERAGENCY WORKGROUP ON AIR QUALITY MODELING (IWAQM) PHASE 2 SUMMARY REPORT AND RECOMMENDATIONS FOR MODELING LONG-RANGE TRANSPORT IMPACTS

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December, 1998

NOTICE

The information in this document has been reviewed in its entirety by the U.S. Environmental Protection Agency (EPA), and approved for publication as an EPA document. Mention of trade names, products, or services does not convey, and should not be interpreted as conveying official EPA approval, endorsement, or recommendation.

PREFACE

The Interagency Workgroup on Air Quality Modeling (IWAQM) was formed to provide a focus for development of technically sound recommendations regarding assessment of air pollutant source impacts on Federal Class I and Wilderness areas. Meetings were held with personnel from interested Federal agencies, viz. the Environmental Protection Agency, the U.S. Forest Service, the National Park Service, and the U.S. Fish and Wildlife Service. The purpose of these meetings was to review respective modeling programs, to develop an organizational framework, and to formulate reasonable objectives and plans that could be presented to management for support and commitment. The members prepared a memorandum of understanding (MOU) that incorporated the goals and objectives of the workgroup and obtained signatures of management officials in each participating agency. Even though no States are signatories, they did participate in IWAQM functions.

This document is being released as a publication of the Environmental Protection Agency (EPA) in response to a request from the members of IWAQM. Members of the workgroup include representatives from the Environmental Protection Agency, the U.S. Forest Service, the National Park Service, and the U.S. Fish and Wildlife Service. The document includes IWAQM's recommendations for modeling methods that might be used to estimate Prevention of Significant Deterioration air quality impacts and National Ambient Air Quality Standards (NAAQS) air quality impacts associated with long-range transport of pollutant emissions to Class I and Wilderness areas . The IWAQM recommends that the CALPUFF Lagrangian puff dispersion modeling system be used for characterization of the transport and dispersion.

The recommendations of IWAQM contained in this document is considered technical guidance tailored for use in assessing air quality impacts associated with prevention of significant deterioration.

ACKNOWLEDGMENTS

The members of IWAQM acknowledge the special efforts by Mark Scruggs, John Notar and John Vimont of the National Park Service; Alan Cimorelli of the U.S. Environmental Protection Agency (EPA); John Irwin of the National Oceanic Atmospheric Administration (NOAA) Air Resources Laboratory; Richard Fisher and Bob Bachman of the U.S. Forest Service; Elwyn Rolofson of the U.S. Fish and Wildlife Service; Patrick Hanrahan of the State of Oregon, Department of Environmental Quality; and Kenneth McBee of the Commonwealth of Virginia, Department of Air Pollution Control for their input and suggestions on assembling this document and their subsequent review. In compiling the reviews of investigations completed that involved in some manner the CALMET/CALPUFF modeling system, various authors graciously provided access to their results and data, and have permitted IWAQM to cite directly from their reports and papers. The IWAQM gives special recognition and thanks to: Andrew Gray of SAI, Inc, John Sherwell of the Maryland Department of Natural Resources, O. Russ Bullock, Jr., Frank Binkowski, and Robin Dennis of the NOAA Air Resources Laboratory, David Strimaitis and Joesph Scire of Earth Tech Inc., Jim Paumier of Pacific Environmental Services Inc., Peter Eckhoff and C. Thomas Coulter of the EPA Office of Air Quality Planning and Standards.

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1.0 INTRODUCTION

Special protection from adverse air quality impacts is afforded certain national parks and wilderness areas, through the prevention of significant deterioration (PSD) program (U.S. EPA, 1980). These areas have been designated as Class I areas, and as such, increases of pollutant levels in these areas are strictly limited. Furthermore, the Federal Land Manager (FLM) of the Class I area is given an affirmative responsibility to ensure that Air Quality Related Values (AQRVs) are not adversely impacted. [The FLMs of the Class I areas are the U.S. Forest Service (USFS), the National Park Service (NPS), and the U.S. Fish and Wildlife Service (FWS).] Air quality models are one of the primary tools used to assess the impacts from sources of air pollution on both the established Prevention of Significant Deterioration (PSD) increments and the AQRVs. Steady-state models have been generally used for PSD analyses. As the PSD program has developed, the need for more sophisticated models to assess air quality impacts in Class I areas, from sources at relatively greater distances from the Class I areas, has arisen. In some areas, the FLMs have asserted that Class I areas have been adversely affected by air pollution and that new sources of pollution over a broad area are further harming the resource. The absence of any recommended long-range modeling techniques has left permitting authorities without the means to assess the assertions of the FLMs. The Environmental Protection Agency (EPA) and the FLMs have undertaken various model development efforts to address the air quality impacts of pollution transported over relatively long distances. The Interagency Workgroup for Air Quality Modeling (IWAQM) was formed to coordinate the independent modeling efforts of the EPA and the FLMs so that a consistent, technically credible approach can be recommended and used.

Models used to evaluate the impact of sources of air pollution on the PSD increments and National Ambient Air Quality Standards (NAAQS), are required to follow Appendix W to 40 CFR Part 51 (*Guideline on Air Quality Models),* U.S. EPA (1997). (Hereafter, referred to as the *Guideline*.) For many situations, preferred models, considered generally applicable under a variety of circumstances, are defined. Currently within the *Guideline* (Section 7.2.6), there is no preferred model listed for assessing impacts involving transport beyond 50 km. For those situations for which there are no preferred models, criteria are established in the *Guideline* to use appropriate methods on a case-by-case basis. These criteria are:

i. The model can be demonstrated to be applicable to the problem on a theoretical basis, and

ii. the data bases which are necessary to perform the analysis are available and adequate, and

iii. performance evaluations of the model in similar circumstances have shown that the model is not biased toward underestimates, or

iv. after consultation with the EPA Regional Office, a second model is selected as a baseline or reference point for performance and the interim procedures are then used to demonstrate that the proposed model performs better than the reference (preferred) model.

The processes which become important in the transport of pollution over long distances include the spatial and temporal variability of the winds which transport and disperse air pollutants in the presence of various terrain and water features, the chemical transformation of the pollutants as they travel, and the deposition of the pollutants along the way. Cummulative impact assessments likely will need to address multiple, geographically disperse sources. There are existing long-range transport models available which meet some, but not, all of these needs and some which meet these needs but either have not been sufficiently tested or are perceived to need further development for routine operational use in regulatory assessment analyses. One of the primary goals of IWAQM is to evaluate existing modeling codes and either recommend one as an accepted approach or combine the better elements of several of the existing codes, creating a new modeling construct.

The IWAQM work plan (U.S. EPA, 1992a) describes a phased approach to satisfy the modeling needs described above. Phase 1 consists of reviewing EPA guidance and recommending an interim modeling approach to meet the immediate need for a long-range transport model for ongoing permitting activity. In developing a Phase 2 recommendation, the workgroup was to review other available operational models and make a recommendation of the most appropriate modeling techniques. The Phase 2 recommendation was to be a compromise between the current modeling state-of-science and best available operational computer capabilities. If resources could be found to pursue a Phase 3 recommendation, the workgroup would add more advanced modeling techniques to its consideration, probably representing a greater level of scientific and computer hardware sophistication.

Given the practical limitations of resources and hardware, the Phase 1 interim recommendations (U.S. EPA, 1993) were designed to provide the best approach from existing "off-the-shelf" techniques. Two models were assessed, the MESOPUFF II model (U.S. EPA, 1994) and the Acid Rain Mountain Mesoscale Model (ARM3), Morris et al., (1988). Upon careful examination of both models, coding errors were discovered in the ARM3, which potentially invalidated its previous evaluations. With this in mind and other considerations as discussed in U.S. EPA (1993), the Phase 1 recommendation was to use on a case-by-case basis the Lagrangian puff model, MESOPUFF II, to evaluate the impacts of pollutants from sources located more than 50 kilometers from Class I areas, up to several hundred kilometers from Class I areas. The impacts are: 1) the allowable Class I increases (increments), 2) the National Ambient Air Quality Standards (NAAQS), and 3) Air Quality Related Values (AQRVs)

associated with emissions of sulfur, nitrogen and particulate matter. The PSD NAAQS pollutants were sulfur dioxide (SO_2) and particulate of size less than or equal to ten microns (PM_{10}). AQRV impacts include such effects as visibility degradation and acidic deposition. In order to focus this effort, increase the chance for success in at least certain scenarios, and to meet an articulated immediate need of permitting authorities and the EPA, IWAQM chose to address only sulfur and nitrogen derived pollutants. It was acknowledged that there are other pollutants such as photochemical oxidants that may injure components of the natural ecosystem, but assessment by IWAQM of the modeling needs and development of oxidant effects modules was postponed until a later date. The Phase I interim recommendations also provided a screening methodology, which (as is discussed later) proved to be too concervative to be of much use.

For the Phase 1 recommendation, MESOPUFF II was deemed suitable for conducting single source impact analyses, and in some circumstances cumulative impact analyses. As the dispersion characterizations in MESOPUFF II were not designed to handle local-scale dispersion effects, it was recognized that the MESOPUFF II results would frequently need to be combined with the results from other modeling techniques used to estimate concentrations from sources closer than 50 kilometers to a receptor area. The Phase 1 recommendation was structured to satisfy case-by-case *Guideline* criteria i, ii, and iii above. The iv criterion has meaning only when there is a preferred model, and such is not the case for modeling impacts involving transport beyond 50 kilometers.

By restricting the models considered for Phase 1 to "off-the-shelf" techniques, IWAQM recognized certain limitations. These include a lack of consideration of the effects of terrain on the long-range transport and dispersion, an underestimation of the conversion of sulfur dioxide, SO_2, to sulfate, $SO_4^=$, when polluted air interacts with clouds, and a possible overestimation of particulate nitrate when a limited number of sources are considered. Nonetheless, IWAQM considered the techniques, suggested to be a significant improvement to those previously used, in that previous techniques ignored many of the processes important to the assessment of air quality impacts in Class I areas. Thus, while under some circumstances the impacts on regional visibility may be underestimated, because the concentrations of sulfates in the atmosphere may be underestimated due to the inability of the model to treat in-cloud processes, IWAQM, including the representatives of the land management agencies, considered the suggested techniques to be technically superior to simply assuming that there are no impacts on regional visibility.

The IWAQM recognized that there were certain risks involved with recommending an interim modeling approach. From a regulatory perspective, it is generally desirable to use an interim model which will yield somewhat higher impact calculations than a more refined, preferred approach. In the case of steady-state air quality models, this can be relatively easily ensured because of the independence of the concentration calculations from one hour to the next. In the case of the Lagrangian

long-range transport models under consideration here, the concentration calculations for a given hour will be explicitly dependent on the spatially and temporally varying wind field from that hour and previous hours. Therefore, the exact behavior of a given modeling system relative to a similar but different modeling system can not be predicted with certainty.

Not long after the release of the Phase 1 recommendation, the EPA sponsored the Sixth Modeling Conference which was held August 9-10, 1995 in Washington, D.C. One of the main topics at this two-day event was a review of IWAQM Phase 1 recommendation, a summary of work in progress, with review comments provided by several groups. At the conference, IWAQM presented long-range trajectory comparison, that suggested that use of mesoscale meteorological analyses of wind fields provided a significant improvement in the accord of modeled and observed trajectories. The IWAQM endorsed specifically the use of mesoscale meteorological analyses that employ data assimilation. The IWAQM recommended that the Phase 1 recommendation to use the MESOPUFF II modeling system be replaced with a recommendation to use the CALMET/CALPUFF modeling system. This was a relatively new Lagrangian puff modeling system, which had additional algorithms to provide simulation of local-scale short-range dispersion using methods already endorsed by the EPA. Thus, use of this newer modeling system allowed one model to be used for all sources in an analysis, regardless of the transport distance involved. The IWAQM also endorsed the formation of public/private committees to manage the myriad of site specific technical decisions that are inherent in assessing mesoscale PSD and AQRV impacts on Class I areas. Appendix D provides a review of the information provided at the Sixth Modeling Conference, a summary of comments received, and IWAQM's response to these comments.

Section 2 presents the Phase 2 modeling recommendation, which represents a compromise between the current modeling state-of-science and best available operational computer capabilities. The IWAQM Phase 2 recommendations are for methods and procedures that might be used to estimate air quality Prevention of Significant Deterioration impacts to increments and AQRVs and National Ambient Air Quality Standards (NAAQS) impacts from pollutant emissions, that due to the transport distances and location are best treated using a long-range transport modeling system. The Phase 2 recommendations are not limited to recommendations on which modeling systems to use, as part of IWAQM's efforts are to assist in fostering best assessment of impacts. Briefly summarized, the Phase 2 recommendation consist of:

- a suggested screening technique for modeling worst-case estimates of long-range transport impacts,

- a recommendation that the CALPUFF modeling system be listed as the preferred model in Section 7.2.6 in the *Guideline*,

- recommendations for assessing PSD increment and NAAQS impacts of a new source's emissions (or change in an existent source's emissions) involving long-range transport of emissions,

- recommendations for assessing the AQRV impacts of a new source's emissions (or change in an existent source's emissions) of sulfur, nitrogen and particulate matter to regional visibility degradation and deposition, which requires a knowledge of the current state of the Class I area, and

- a recommendation that consideration be given to forming committees ('Regional Approach') to assist in the resolution of the myriad of decisions associated with mesoscale modeling of PSD and AQRV impacts for each Class I area (or groups of areas).

Section 3 discusses the chemistry limitations inherent in CALPUFF, and how results from CALPUFF can be used to estimate regional visibility impacts and deposition of sulfur and nitrogen.

From the comments received at the Sixth Modeling Conference, IWAQM concluded that in order to provide a firmer basis for a Phase 2 recommendation, more information was needed comparing mesoscale modeling dispersion results with tracer field data, and more comparisons were needed to stress test code modifications made to incorporate local-scale dispersion characterizations. Everyone was in agreement that the screening analysis, suggested by IWAQM in the Phase 1 recommendation, was inadequate. It was perceived as providing such large overestimates of SO_2 and sulfate impacts that it was of little use. Section 4 provides a review of the activities that IWAQM has sponsored in developing the Phase 2 recommendations, as well as, summaries of investigations that IWAQM is aware of that provide information regarding lessons learned in using and applying the CALPUFF modeling system.

2.0 MODELING RECOMMENDATIONS

For most of the modeling situations discussed in the *Guideline* where a refined modeling technique is recommended, a screening analysis is also provided. The screening analysis is meant to be easy to conduct and to provide a worst-case maximum impact estimate. If the results of the screening analysis show compliance with existing regulatory requirements, then no further modeling for compliance with standards and increments is required.

Basically, IWAQM's recommendations for a screening analysis is an approach of using a simplified set of meteorology with CALPUFF. To encourage the results to be higher than would be estimated using a fully developed CALMET and CALPUFF analysis, rings of receptors are used. The maximum concentration value found anywhere on the receptor rings are used (rather than restricting the analysis to receptors only located within the Class I area(s) of interest). More discussion of the steps to be taken and processing requirements for a screening analysis is provided in Section 2.1.

IWAQM's recommendations for a refined analysis involve the following differences from the screening analysis:

- use of a fully developed time and space varying characterization of the meteorology using CALMET, and
- the receptors are placed within the Class I area(s) of concern, and
- the background concentrations of ozone and ammonia are allowed to vary in time and space, and
- the concentration and AQRV impacts are computed to more directly correspond to the standards, increments, and thresholds of concern.

More discussion of the steps to be taken and processing requirements for a refined analysis is provided in Section 2.2.

Sections 2.1 and 2.2 focus on how to apply models, specific options and data sets to be employed, and the processing of the input and output data. Section 2.3 provides more general recommendations on practical issues and limitations of long-range transport modeling assessments.

2.1 Screening Analysis

Section 4.7 presents comparisons of puff and plume model simulation results to demonstrate what differences might arise in simulated concentration values when the plume and puff model employ essentially identical meteorology and dispersion characterizations. The results shown in Section 4.7 show striking evidence that treating the sequence of meteorological events of all hours (including calms), can result in puff simulated maxima that are considerably higher than plume simulated maxima for

almost any distance downwind or averaging time. This was most evident for the shorter averaging times that were 24-hours or less. The IWAQM concludes from these results that use of a plume model as a screen for a puff model's impacts is unlikely to be successful. In Section 4.8, a summary is presented of comparisons of results obtained by using a puff model with single station meteorology (a screening analysis) versus fully generated wind fields (a refined analysis) for each hour. These results suggest that the maximum concentration values simulated using the proposed screening approach for a receptor ring may occasionally underestimate results obtained from a refined model simulation. To address this tendency, IWAQM recommends use of the maximum concentration found anywhere on the receptor rings, rather than limiting the analysis to only receptors within the Class I area(s) of concern (as would be the case in a refined analysis). These conclusions are for maxima on receptor rings at fixed distances from isolated point sources where the terrain was relatively flat.

.

With these thoughts in mind, the following CALPUFF screening procedure is suggested by IWAQM (as outlined in Table 1):

1) generate five years of ISCST3 input meteorology using PCRAMMET,

2) generate an ISCST3 control file (use standard ISC defaults and create receptor rings as appropriate for the application); use the ISC2PUF conversion program to create the CALPUFF control file,

3) edit the CALPUFF control file to select MESOPUFF II chemistry, and specify domain-wide background concentration values for ozone and ammonia (see Section 2.2.2),

4) run CALPUFF with the ISCMET.DAT data option, and pick the maximum concentration for each pollutant, for each receptor ring and averaging time modeled. Perform increment and AQRV comparisons as required. For haze impact assessment, use the FLM provided "clean" background extinction coefficient and assume a RH value of 90%.

In Step 1 above, it is anticipated that an update will be made to PCRAMMET and the Meteorological Processor for Regulatory Modeling (MPRM) so that they will list the relative humidity for each hour, along with the other parameters needed to compute deposition. With this update, the MESOPUFF II chemistry can be activated within CALPUFF. In Step 2 above, it is envisioned that receptor rings would be created that would pass through the Class I area(s) of interest. The IWAQM recommends that the placement of the receptor rings, and assumptions to be employed in the CALPUFF model runs be discussed with the applicable reviewing authorities, prior to actually

Table 1. Outline of recommendations for screening analysis. Given judgement required in receptor ring placement and background values to be assumed in CALPUFF and CALPOST analyses, applicants should gain agreement on how coordination with Federal Land Managers (FLM) and other reviewing authorities will be addressed, prior to conducting runs and analyses.	
Meteorology	Use five years of PCRAMMET (extended output for deposition).
Receptors	Receptors at least every two degrees on rings that encircle source and pass through the Class I area(s) of interest.
Dispersion	1. Use ISC2PUF to convert an ISC3 control input file for use by CALPUFF. 2. Edit control file to use MESOPUFF II chemistry; use wet and dry deposition (use default setups for these). 3. Use domain average background values for ozone and ammonia for area. 4. Run CALPUFF using ISC meteorology option (note, define 6 to 10 layers in vertical; top layer should extend above maximum mixing depth expected); horizontal domain extending 50 to 80 km beyond outer receptor ring.
Processing	**1. For PSD increments**: use maximum 3-hr, 24-hr and annual SO_2 and PM_{10} and maximum annual NO_2 for comparison with allowable limits. **2. For haze:** use maximum 24-hr $SO_4^{=}$, NO_3^{-}, and HNO_3 values; assume 90% RH for f(RH) for day, calculate extention coefficients for each pollutant (see Section 3.2); and compute the precent change in extinction using the FLM supplied background extinction, as described in Section 3. **3. For total S or N deposition:** convert deposition flux to kg/(hectar•year) using maximum values of annual SO_2, $SO_4^{=}$, NO_3^{-}, HNO_3, and NOx as described in Section 3.

conducting any screening analyses. These up front discussions are essential for defining the AQRV's of interest, which dictate the averaging times and pollutants of interest for the AQRV assessments. The maximum 3-hr, 24-hr and annual SO_2 and PM_{10}, and the annual nitrogen dioxide concentrations would be compared with the current standards and PSD increments as required by the applicable reviewing authorities. If a haze impact assessment is required, then use the 24-hour maximum sulfate, nitrate and primary particulate concentrations in equation (8) of Section 3.2. If total nitrogen or total sulfur deposition impacts are required, then use the maximum annual concentration values and follow the procedures as described in Section 3.3.

2.2 Refined Analysis

Table 2 outlines the basic IWAQM recommendations for a refined analysis. It is understood that conducting a CALMET and CALPUFF analysis for any scale of application will necessarily involve case-specific judgements. It is IWAQM's conclusion that it is not possible to prescribe all the decisions needing to be made. We have attempted to provide suggestions where possible. We have recommended that all users of CALMET and CALPUFF start with a common set of default conditions and input data. Then, as the decisions are made to change default settings and discard or augment the input data, these can be discussed and reviewed with the applicable authorities, prior to actually committing expensive and time-consuming resources. Within this context use of technical review committees, as suggested in the Regional Approach (Section 4.5), would greatly assist applicants in these endeavors.

2.2.1 Meteorology

<u>Expertise Needed</u>

Currently, developing CALMET meteorological fields is considered a difficult task just managing the sheer volume of input and output data of CALMET, and excellent computer skills are needed to manage the operation of the various processors to CALMET. The software was not written to accept a variety of input data formats. The software was developed with the assumption that the user is capable of screening the data for anomalous values. It was assumed that if the data are not in the required format, the user has the programming skills to write special programs to translate the data format to the format required.

Renovating these programs was beyond the resources available to IWAQM. The IWAQM focused what resources it had to the issues of testing the technical aspects of the modeling system (comparisons with tracer experiments, enhancement of processing controls, etc.) to see if the CALMET/CALPUFF modeling system was technically sufficient for routine use. It has been assumed that support to renovate these processors can be found, if and when, the CALMET/CALPUFF modeling system becomes a recommended modeling approach.

Currently, adjusting and tailoring the CALMET options to see if the generated wind fields are reasonable requires strong computer graphics skills to visualize the results generated by CALMET. This component of the analysis can be simplified by using existing visualization software.

The control of the CALMET options requires expert understanding of mesoscale and microscale meteorological effects (such as terrain slope flows) on meteorological

Table 2. Outline of recommendations for refined analysis. Given judgement required in CALMET, CALPUFF and CALPOST processing, applicants must gain agreement on how coordination with Federak Land Managers (FLM) and other reviewing authorities will be addressed, prior to conducting runs and analyses.	
Meteorology	1. Use five years of representative hourly NWS surface and precipitation observations, and twice-daily upper air observations. On a case-by-case basis, one may use less than five years of *FDDA-MM* data with representative NWS data; or use less than five years of on-site meteorological data with available NWS data. 2. CALMET (minimum of 6 to 10 layers in vertical; top layer must extend above maximum mixing depth expected); horizontal domain extending 50 to 80 km beyond outer receptors and sources being modeled; terrain elevation and land-use data resolved for situation (tailor land-use parameters to situation).
Receptors	Within Class I area(s) of concern, provide coverage tailored to situation (insure FLMs concur).
Dispersion	1. CALPUFF with default dispersion settings. 2. Use MESOPUFF II chemistry; use wet and dry deposition (use default setups for these). 3. Define background values for ozone and ammonia for area (tailor spatial variability to situation needs and data availability).
Processing	**1. For PSD increments:** use highest second-highest 3-hr, 24-hr concentration values, and use the maximum annual concentration values of SO_2 and PM_{10} and maximum annual for NO_2 for comparisons with allowable limits. **2. For haze**: process the 24-hr $SO_4^=$, NO_3^-, and HNO_3 values adjusted using hourly RH as discussed in Section 3; calculate extinction coefficients for each pollutant (Section 3.2), compute the percent change in extinction using the FLM supplied background extinction, as described in Section 3; compare with thresholds as directed by applicable FLMs and reviewing authorities. **3. For total S or N deposition:** convert deposition flux to kg/(hectar•year) using maximum values of annual SO_2, $SO_4^=$, NO_3^-, HNO_3, and NOx as described in Section 3; compare with threshold as directed by applicable FLMs and reviewing authorities.

conditions, and finesse to adjust the available processing controls within CALMET to develop the desired effects (e.g., Section 4.9.2). The IWAQM does not anticipate a lessening in this required expertise in the future. Developing three-dimensional time-varying fields of meteorological conditions is a demanding task, which can not be left to unskilled or inexperienced staff. The IWAQM does not foresee a time when

development of time-varying mesoscale meteorological wind fields (by whatever means) will become as simplified as the running of the ISC3 modeling software has become in recent years.

Appendix A provides a listing of the default settings recommended by IWAQM at this time. Some of these settings require testing, and we have attempted note these. The information provided in Appendix A should not be interpreted as a cookbook approach to be applied, regardless of results obtained.

Length of Modeling Assessment

Significant year-to-year variations were seen in the Demonstration Assessment (Section 4.1) and also in the developmental work towards attempting to build a new screening methodology (Section 4.8). These results suggest that several years of refined analysis are needed to address the variation in pollution impacts likely to occur. For consistency with other *Guideline* requirements, a five-year period of analysis using representative NWS meteorological data is recommended. CALMET employs diagnostic algorithms to tailor the available meteorological data for slope flow effects, land-sea circulations, etc. If special meteorological observations are available within the modeling domain that would assist CALMET's diagnostic analysis, or if *FDDA-MM* data are to be employed in the CALMET analysis, then less than a five-year period of analysis can be accepted, on a case-by-case basis by the applicable reviewing authorities. This accommodates use of refined meteorological data for those locations where refined meteorological data have been suitably processed, or where mesoscale meteorological campaigns have been accomplished.

Geophysical Data

Terrain heights and land-use are needed for input to CALMET. The IWAQM has provided one set of these values for the contiguous United States. The grid resolution is approximately 900 m for the terrain data and 1/12 degree latitude (9.25 km) by 1/8 degree longitude (9.8 km at 45° latitude) for the land-use data (CALMET, CALPUFF, And CALPOST Modeling System (Version 1) CD-ROM; see Appendix C). Default values characterizing the surface parameters associated with each land-use class are also provided. The resolution of this data set is considered adequate for assessments involving transport distances of 50 km and greater, although the land-use categorization should be examined carefully. The resolution of this data set may also be adequate for many local-scale assessments.

The IWAQM recommends use of this data set, as a first choice. The IWAQM recognizes that there are instances when these terrain heights and land-use data must be considered inappropriate, such as the situation discussed in Section 4.9.2. It is anticipated that rejection of this data set will most often be for treatment of sources located in very rugged terrain, which is anticipated to significantly affect the transport trajectory of the plume. Using this data set, as a first choice with assignment of the

default surface parameters as listed on the distribution CD, should provide consistency in future analyses and helps to standardize the input requirements for software development.

Another source of terrain heights and land-use data is from the United States Geological Survey (USGS). Some of these data can be accessed through the World Wide Web. The general USGS site is at http://www.usgs.gov. At the time of this writing, the data was available at http://edcwww.cr.usgs.gov/doc/edchome/ ndcdb/ndcdb.html.

Precipitation Data

Precipitation is notoriously spotty, with many localized maxima and minima. It is recommended by IWAQM that all precipitation reports reasonably available be used.

Precipitation data are available for the United States from the National Climatic Data Center (NCDC) in a format called TD-3240. No data filling is necessary for these data sets for use by CALMET. But as discussed in EPA (1995a), the formatting of these data for a large domain is not trivial. The software available is not robust and could stand to be improved.

Another source of precipitation data is from private firms that purchase the data from NCDC, repackage it, and provide software for extracting the repackaged data. This may be an attractive alternative to some users.

National Weather Service Data

The number of surface and upper air sites will be determined by the size of the modeling domain and the availability of meteorological data. It is recommeded that for refined analyses one would use all sites that are within and near the modeling domain, so as to provide as good a characterization as possible of the spatial variation of the meteorological conditions.

The CD-ROM data sets (Appendix C) are made available by the National Climatic Data Center. These hourly surface weather observations (*Solar and Meteorological Surface Observation Network* (SAMSON) and Hourly United State Weather Observations (HUSWO) 1990-1995), and twice-daily upper air observations (*Radiosonde Data for North America*) are recommended by IWAQM as first choice for acquiring access to these data. Using these data sets, as a first choice, should provide consistency in future analyses and helps to standardize the input requirements for software development.

The current CALMET software requires the user to closely inspect the upper-air data prior to use. Since the program does not fill in missing levels or time periods (which sometimes occur in the observations), the user should inspect the data to insure

that complete data is available at least for all levels below and just above the anticipated maximum mixing depth for the modeling domain. Furthermore, CALMET can not process if the time difference between successive upper-air soundings is greater than 12 hours. If this occurs, the user must use judgement to fill in the requisite data. When multiple NWS sites are used for characterizing the hourly surface weather conditions, missing observations from one station can be handled simply by filling in a missing data indictor for that site for that hour. But the user should review the hourly surface observations to insure that the data coverage in space and time is adequate. This requires judgement and finesse and given the complexities of long-range transport analysis, is not amenable to cookbook cures.

FDDA-MM Data

As mentioned in Section 4.4 there are various groups capable of developing *FDDA-MM* data suitable for use as input to the CALMET/CALPUFF modeling system. Alternatively, consideration could be given to using the 1990 MM4 data set (NCDC, 1995) or other data sets which might be completed for other years. The problem with these data sets is that the they are costly to construct and advances are currently being made at such a rapid pace, they are becoming dated almost as soon as they are constructed. Furthermore, there are situations defined in the *Guideline* when on-site meteorological data are to be collected and used in the modeling assessments (e.g., when using CTDMPLUS for a complex terrain impact assessment, where the transport distances are less than 50 km). Hence, there appears to be a never-ending need to construct additional years of data. The IWAQM recommends finding a link to some operational source of *FDDA-MM* data, as the optimal solution.

Towards this end, IWAQM recommends that links to the operational model outputs that are produced by the NOAA Mesoscale Modeling Branch (MMB) (see discussion by Schulze and Turner, 1998). This group is developing data suitable for use in the CALMET/CALPUFF modeling system. They have an active plan to refine and improve the modeling science and to reduce the grid size in future years. These model outputs are being developed to directly support operational needs of the National Weather Service, and should prove to be a stable source of such data in the future.

The major obstacle is access to these data. An operational means for gaining easy access to comprehensive mesoscale meteorological data sets has yet to be developed. Therefore, IWAQM recommends that a solution be developed that will provide the public routine, inexpensive access to such data. The data can be depended on being available in future years. Users who either are required to collect and use on-site data, or need such data for best characterization of their situations, can use CALMET to manage the blending of their on-site data, with routine NWS observations and available *FDDA-MM* data.

Once an operational link is established to an operational source of *FDDA-MM* data and a sufficiently long record of the data is available, IWAQM recommends the use of these data.

2.2.2 Chemistry

The MESOPUFF II chemistry option, currently available in CALPUFF, is adequate for representing gas phase oxidation of sulfur dioxide to sulfate and for the nitrate chemistry. The algorithms currently do not adequately account for the aqueous phase oxidation of sulfur dioxide to sulfate. The aqueous phase chemistry can dominate the formation of sulfate. Therefore, in many applications sulfate is likely to be underestimated.

The IWAQM recommends use of the MESOPUFF II chemistry option, although it is recognized that this module may grossly underestimate the conversion of sulfur dioxide to sulfate when the pollutants interact with clouds or fog.

Ozone Background

CALPUFF provides two options for providing the ozone background data: (1) a single, typical background value appropriate for the modeling region, or (2) hourly ozone data from one or more ozone monitoring stations. The second and preferred option requires the creation of the OZONE.DAT file containing the necessary data. For the Demonstration Assessment, the domain was large (700 km by 1000 km) such that the second option was necessary. The IWAQM does not anticipate such large domains as being the typical application. Rather, it is anticipated that the more typical application will involve domains of order 400 km by 400 km or smaller. But even for smaller domains, the ability to provide at least monthly background values of ozone is deemed desirable. The problem in developing time (and perhaps spatial) varying background ozone values is having access to representative background ozone data.

Ozone data are available from EPA's Aerometric Information Retrieval System (AIRS); however, AIRS data must be used with caution. Many ozone sites are located in urban and suburban centers and are not representative of oxidant levels experienced by plumes undergoing long range transport.

Ammonia Background

A further complication is that the formation of particulate nitrate is dependent on the ambient concentration of ammonia, which preferentially reacts with sulfate. The ambient ammonia concentration is an input to the model. Accurate specification of this parameter is critical to the accurate estimation of particulate nitrate concentrations. Based on a review of available data, Langford et al. (1992) suggest that typical (within a factor of 2) background values of ammonia are: 10 ppb for grasslands, 0.5 ppb for forest, and 1 ppb for arid lands at 20°C. Langford et al. (1992) provide strong evidence

that background levels of ammonia show strong dependence with ambient temperature (variations of a factor of 3 or 4) and a strong dependence on the soil pH. However, given all the uncertainties in ammonia data, IWAQM recommends use of the background levels provided above, unless specific data are available for the modeling domain that would discredit the values cited. It should be noted, however, that in areas where there are high ambient levels of sulfate, values such as 10 ppb might overestimate the formation of particulate nitrate from a given source, for these polluted conditions. Furthermore, areas in the vicinity of strong point sources of ammonia, such as feed lots or other agricultural areas, may experience locally high levels of background ammonia.

2.2.3 Dispersion

Expertise Needed

The control of the CALPUFF options requires expert understanding of terrain affects on meteorological conditions and some finesse to adjust the available processing controls. Appendix B provides a listing of the default settings for CALPUFF recommended by IWAQM at this time. Some of these settings require testing, and IWAQM has attempted note these. The information provided in Appendix B should not be interpreted as a cookbook approach to be applied, regardless of results obtained.

Emissions

Developing an inventory with agreed upon emission rates is not trivial. The inventory could differ depending on whether the analysis is addressing NAAQS assessments (which typically address maximum allowable emission rates from only PSD sources) versus AQRV assessments (which typically address actual current emission rates from all existing sources). The IWAQM recommends that the manner in which the sources and emissions are to be characterized be agreed upon in the initial up-front discussions with the reviewing authorities.

Receptors

For some Class I areas the FLMs have developed receptor networks for use in the modeling analyses, which facilitates assessment of cumulative impacts from successive applicants. In such cases, the applicants should use these predefined receptor networks. In other situations, IWAQM suggests use of judgement. The more rugged the terrain and the presence of local sources being included in the analysis will necessitate use of more closely spaced receptor networks in order to adequately characterize the concentration patterns to be simulated for the Class I area(s). This is another area where judgement and review by others will be needed.

Local-scale

The IWAQM is recommending use of the CALPUFF modeling system for the characterization of all sources being explicitly modeled. This eliminates the need to simulate the long-range impacts (those involving transport greater than 50-km) separately, and then combine these results with those obtained using some other model for the local-scale impacts (those involving transport of less than 50-km). We have CALPUFF and ISC comparison results using both steady-state and non-steady-state hourly meteorology. It was the conclusion of IWAQM that CALPUFF could reproduce the steady-state results of the ISC plume dispersion model. A benefit of using one model for all sources is that CALPUFF has the MESOPUFF II chemistry, which provides characterization of pollutant species that are not treated by currently available local-scale models (such as ISC and CTDMPLUS).

Comprehensive tests results are not available comparing CALPUFF with CTDMPLUS for steady-state impacts on isolated hills and ridges. The IWAQM assumes that once these have been accomplished and the results have been shown to be similar, that long-range impact assessment with CALPUFF (using fully developed CALMET meteorology) can also include more explicit hill impaction assessments, as necessary, for all sources regardless of the transport distances involved.

2.3 Practicalities

The IWAQM recommendations for conducting a long-range transport screening analysis are presented in Section 2.1, and the IWAQM recommendations for conducting a long-range transport refined analysis are presented in Section 2.2. The focus of these discussions was how to run the simulations and the management of the input and output data. There are other practical concerns that applicants and reviewing authorities should be mindful of, namely: the uncertainties associated with the screening analysis, the uncertainties associated with the refined analysis, differences between plume and puff simulation results, and commensurate difficulties in providing technical oversight.

2.3.1 Screening procedures uncertainties

In Section 4.8 comparisons are presented of CALPUFF simulation results generated either through the use of ISC or CALMET meteorology. Anticipating that most analyses will involve a moderate to tall stack, of order 35-m to 200-m in height, it is seen that the screening estimates of sulfur-dioxide and sulfate concentration maxima obtained using ISC meteorology, typically range within ±70% of that simulated using CALMET meteorology. The sulfur dioxide and sulfate deposition fluxes obtained using ISC meteorology, typically range within ±60% of that simulated using CALMET meteorology. This suggest that the screening analysis as proposed is not providing a biased (overestimate) of these impacts. It was for this reason that IWAQM recommended that all receptors on the ring be included in the screening assessment. It

was hoped that this would provide a measure of conservatism to the screening analysis. Adding a measure of conservatism is deemed reasonable, as the proposed screening analysis completely disregards the terrain and land-use induced wind effects, that would arise if fully-developed three-dimensional wind fields were developed using available surface and upper-air observations. The IWAQM concludes that the impacts estimated by the screening procedure proposed are conservative and yet less onerous than results as would be obtained by the Phase 1 Level 1 screening, and addresses concerns raised at the Sixth Modeling Conference

2.3.2 Refined modeling uncertainties

In Section 4.6 comparison results of CALPUFF simulations with tracer field data are provided. The studies presented are considered representative of a few of the better tracer field studies that involve comprehensive sampling along arcs at downwind distances of order 50- to 100-km. As summarized in Section 4.6, in general the CALPUFF simulated concentration values were within a factor of two of that observed. Little differences in overall performance was seen, whether Pasquill or similarity dispersion curves were employed. This is understandable since as transport times and distances increase, the dispersing material is becoming well-mixed in the vertical, and the horizontal extent of the dispersing material is more related to the wind field variations than is the rate of relative dispersion about simulated puff centroids. This is dramatically made apparent by the results shown in Section 4.7, where direct comparisons were made of the ISC plume model and CALPUFF. In these comparisons it was shown that for steady-state assumptions, CALPUFF could suitably mimic results as would be obtained by ISC. And yet with identical specification of the dispersion and meteorology, once the puff model was allowed to simulate the ‘causality’ of hour-by-hour variations, the puff model’s results no longer were similar to that obtained by ISC. In fact, as a result of explicitly treating calms and wind reversal effects by the puff model, the simulated maximum concentrations by CALPUFF were generally greater than that simulated by ISC for all transport distances and averaging times.

The quality and uncertainties associated with long-range transport simulations is driven more by the characterization of the mixing depth and by the characterization of the transport winds. Better characterization of the mixing depth may be possible in the future, but it should be understood that the mixing in the vertical reflects both local and mesoscale effects. The influence of local variations in land-use (forests, lakes, farmland, cities) can be significant. Hence uncertainties of order ±40% in mixing depth are likely (Irwin and Paumier, 1990) and will be difficult to avoid. Improvement in the characterization of the transport winds is possible through the use of *FDDA-MM* meteorological data, as discussed in Section 4.3. Both the comparisons of simulated trajectories and the comparisons of trajectories derived using the CAPTEX tracer field show improvement through the use of sophisticated mesoscale meteorological data employing FDDA.

Based on the tracer comparison results presented in Section 4.6, it appears that CALPUFF provides reasonable correspondence with observations for transport distances of order 100 km. Most of these comparisons involved concentration values averaged over 5 to 12 hours. The CAPTEX comparisons, which involved comparisons at receptors that were 300 km to 1000 km from the release, suggest that CALPUFF tends to overestimate surface concentrations by a factor of 3 to 4. Use of the puff splitting option in CALPUFF might have improved these comparisons, but there are serious conceptual concerns with the use of puff dispersion for very long-range transport (300 km and beyond). As the puffs enlarge due to dispersion, it becomes problematic to characterize the transport by a single wind vector, as significant wind direction shear may well exist over the puff dimensions.

With the above thoughts in mind, IWAQM recommends use of CALPUFF for transport distances of order 200 km and less. Use of CALPUFF for characterizing transport beyond 200 to 300 km should be done cautiously with an awareness of the likely problems involved. Since the long-range transport results appear to be relatively insensitive to the exact selection made for characterizing the puff dispersion parameters, IWAQM recommends use of dispersion parameters that provide results most similar to the local-scale model of choice (which currently is ISC). It would appear that CALMET is capable of treatment of highly complex wind fields that are strongly influenced by terrain slope flows (Section 4.9.2). However, as mentioned at the Sixth Modeling Conference, there are situations that one can imagine involving highly rugged terrain, that any model simulation's results must be viewed as uncertain.

2.3.3 Secondary pollutant uncertainties

The CALPUFF simulation for gas phase oxidation of sulfur dioxide to sulfate and for the nitrate chemistry is considered adequate. The algorithms currently do not adequately account for the aqueous phase oxidation of sulfur-dioxide to sulfate, which can become dominant in the presence of fog or clouds. Even if planned updates to CALPUFF include consideration of the aqueous phase chemistry, the input data may preclude routine use of this enhancement. Finally, it must be mentioned that evaluation studies have not been conducted regarding CALPUFF's simulations of secondary formed sulfate and nitrate. The IWAQM is not aware of comprehensive tracer-field-data studies that would lend themselves to such evaluation studies. Given that aqueous phase chemistry is not treated, it is likely that CALPUFF simulations of sulfate would be less than observed. Mention is made in Section 4.9.1 that the total nitrogen deposition estimates by CALPUFF were about a factor of 3 less than estimates provided by a more physically complete model (RADM). Notwithstanding these obvious deficiencies, IWAQM recommends use of CALPUFF's estimates of sulfate and nitrate for purposes of addressing the need to assess AQRV impacts in Class I areas (in lieu of assuming that there are no impacts at all).

2.3.4 Technical oversight and review

It would be convenient if objective criteria and cookbook procedures could be constructed that would preclude inappropriate application of air dispersion models. This has proved to be troublesome for local-scale modeling, and likely is impossible for mesoscale and long-range transport modeling. As in any air quality simulation, the usefulness of the results obtained depends mostly on the expertise brought to the analysis in characterizing the situation, and on the experience applied in interpreting the results obtained. In response to these considerations, IWAQM has attempted to warn the modeling community that conducting a long-range transport assessment requires esperts. We have also tried to warn the modeling community that application of the CALPUFF modeling system to any situation will require expert judgment, it will likely involve site-specific decisions, and it will require strong interaction and coordination with the applicable reviewing authorities.

In this regard, the use of technical review committees, as suggested in the Regional Approach (Section 4.5) would likely prove useful to both the applicants and to the reviewing authorities. These technical committees could assist in sorting through the site-specific decisions, and they could provide a forum for reaching consensus. Having a standing technical committee would provide applicants with some assurance of being treated equitably, and could provide data sets for use to facilitate comparability between individual analyses. Whether such a committee would prove useful is dependent on availability of experts and on the ability to obtain long-term commitments of service. Furthermore, not all Class I areas will require use of such committees. Hence, while IWAQM endorses the use of such committees, IWAQM does not recommend Federal agencies mandate or require their use.

3.0 TRANSFORMATIONS, VISIBILITY, AND DEPOSITION

In principle, estimating the impact of emissions from an individual source is best accomplished using a Lagrangian dispersion model, as a Lagrangian model 'follows' the emissions as they are transported downwind. This provides within the model the ability to directly assess how much each source's emissions are impacting each receptor in the analysis. However, there are some physical processes (like nonlinear chemical transformations) that can be more explicitly and completely characterized using Eulerian grid modeling techniques. To treat nonlinear chemical transformations within a Lagrangian modeling framework is presently so computationally demanding as to be impractical for routine use.

The IWAQM recognized these limitations and tradeoffs between Lagrangian and Eulerian grid modeling techniques. The purpose of the Phase 2 recommendations was to recommend techniques useful for permitting individual PSD sources. For individual source impacts involving complicated terrain and transport distances of order 50 to 250 km, a Lagrangian puff model like CALPUFF is an optimal choice. In this section we summarize the approximations made in the CALPUFF chemical transformations and associated inherent limitations. We then summarize the methodology recommended for computing haze and deposition impacts in Class I areas. Finally, we discuss conceptually how assessment of adverse impact of Air Quality Related Values is somewhat different than traditional NAAQS assessments.

While drafting this report, the National Park Service, the U.S. Fish and Wildlife Service and the U.S. Forest Service have been holding intensive meetings to promote a greater consistency in the procedures Federal Land Managers use in identifying and evaluating AQRV impacts. We have discussed in this report the assessment of regional visibility impacts using the deciview, which at the time of the drafting of this report was the preferred metric. As time progresses, it is looking more like the change of extinction may become the preferred metric. Hence, although the information provided here is useful, the details and implementation may be somewhat different as a consequence of the ongoing discussions. For the latest information on procedures and metrics, we suggest visiting the web site: **http://www.nature.nps.gov/ard/flagfree/index.html**.

3.1 Chemical Transformations

The MESOPUFF II chemistry option, currently available in CALPUFF(4.0), is adequate for representing gas phase oxidation of SO_2 to $SO_4^=$ and for the nitrate chemistry. The algorithms currently do not adequately account for the aqueous phase oxidation of SO_2 to $SO_4^=$. The aqueous phase chemistry can dominate the formation of sulfate. Therefore, in many applications sulfate is likely to be underestimated. A further complication is that the formation of particulate nitrate (NO_3^-) is dependent on the ambient concentration of ammonia, which preferentially reactswith $SO_4^=$. The ambient ammonia concentration is an input to the model. Appropriate specification of this

parameter is critical to the estimation of realistic values of particulate nitrate concentrations.

For instance, if we were simulating effects of emissions coming from an as yet to be built new single source, then the ammonia available to react with these new emissions could be estimated from monitored background levels of ammonia. If there are large major sources near the proposed new source included in the analysis, then the background ammonia should in principle be adjusted to a value somewhat above that monitored to reflect ammonia available that these existing sources typically scavenge from the atmosphere. By way of this example, we see that CALPUFF is most easily applied for isolated new emissions, and becomes more problematic as the number of sources increases. This supports limiting application of CALPUFF to a relatively few sources of emissions, so that the 'background' levels of ozone and ammonia can be derived using appropriate monitoring data.

The spatial and temporal scales, where CALPUFF might be used, are long enough so that the chemical conversion of SO_2 to $SO_4^=$ and NO_X to HNO_3 are of interest. The oxidation of SO_X and NO_X may occur by gas and aqueous phase reactions. The gas phase reactions for both SO_X and NO_X involve free radical photochemistry and, therefore, are coupled to the oxidation of reactive organic gases (ROG). Homogeneous gas phase reaction is the dominant SO_2 oxidation pathway during clear, dry conditions. Ozone and hydrogen peroxide are believed to be the principal oxidants for aqueous phase oxidation of SO_2. Homogeneous gas phase reactions may convert SO_2 at most a few percent per hour, whereas aqueous phase reactions can convert SO_2 up to 100% per hour.

The oxidation of NO_X is dependent on gas phase ROG/NO_X/O_3 photochemistry. It is generally more rapid than SO_2 gas phase oxidation. NO_X can be oxidized to nitric acid (HNO_3) and organic nitrates (RNO_3) such as peroxyacetylnitrate (PAN). HNO_3 combines with ammonia gas to form solid or aqueous ammonium nitrate (NH_4NO_3). Unlike sulfate formation, the nitrate process is reversible. Equilibrium is established between nitric acid, ammonia, and ammonium nitrate:

$$NH_4NO_3 \leftrightharpoons HNO_3 + NH_3$$

The equilibrium constant for this reaction is a nonlinear function of temperature and relative humidity. The equilibrium constant can vary several orders of magnitude over a typical diurnal cycle. Given fixed amounts of total nitrate, ammonia, and water vapor, higher NH_4NO_3 concentrations are expected at night due to lower nighttime temperatures and higher relative humidities. Thus, the nitrate aerosol can not be considered a stable product like sulfate.

The transformation rate expressions, used in the MESOPUFF II algorithm, were developed statistically analyzing hourly transformation rates produced by a

photochemical model. Plume SO_X/NO_X dispersing into background air containing ozone and reactive hydrocarbons was simulated over a wide range of conditions representing different solar radiation intensities, temperatures, dispersion conditions, background ozone concentration and surface-level relative humidity, RH, plume NO_X concentrations and emissions times. The following transformation rate expressions, representing curve fits to the daytime hourly conversion rates predicted by the photochemical model, were determined:

$$k_1 = 36R^{0.55}[O_3]^{0.71}S^{-1.29} + k_{1(aq)}$$
$$k_2 = 1206[O_3]^{1.5}S^{-1.41}[NO_x]^{-0.33}$$
$$k_3 = 1261[O_3]^{1.45}S^{-1.34}[NO_x]^{-0.12}$$

Where,

k_1	is the SO_2 to $SO_4^{=}$ transformation rate (percent/hour),
k_2	is the NO_X to HNO_3 + RNO_3 transformation rate (percent/hour),
k_3	is the NO_X to HNO_3 (only) transformation rate (percent/hour),
R	is the total solar radiation intensity (kw/m^2),
S	is a stability index from 2 to 6 (PG stability A&B = 2, C=3, etc.,
RH	is the surface-level relative humidity (percent),
$[O_3]$	is the background ozone concentration (ppm),
$[NO_X]$	is the plume NO_X concentration (ppm), and,
$k_{1(aq)}$	is the aqueous phase SO_2 oxidation term.

The term, $k_{1(aq)}$ peaks at a value of 3 percent/hour at 100% relative humidity. This is much less than might be expected if the plume interacted with clouds or fog. These transformation rate expressions only apply during the day. At night oxidation rates of 0.2% and 2.0% for SO_2 and NO_X, respectively, are suggested as default values in the model.

3.2 Visibility Analysis

In the context of the Phase 2 recommendation, the focus of the visibility analysis is on haze. These techniques are applicable in the range of thirty to fifty kilometers and beyond from a source. At source-receptor distances less than thirty to fifty kilometers, the techniques for analyzing visual plumes (sometimes referred to as ‘plume blight’) should be applied.

There are two approaches to determining visibility effects (NAPAP Report to Congress). One is a technically rigorous, complex, and situation-specific method, while the other is a more generalized approach. The more rigorous approach requires the calculation of aerosol growth dynamics and the application of Mie theory to determine the optical characteristics of the aerosol distribution. Sophisticated radiative transfer models are then applied, using the aerosol optical characteristics, the lighting and scene characteristics and the spatial distribution of the pollutants to calculate the path

and wavelength of image-forming and non-image-forming light that reaches a specific observer at a specific time and date from all points in the scene being viewed. While this detailed analysis may be useful for assessing specific cases, it is impractical for addressing haze issues where visibility is experienced in a nearly infinite variety of situations and where detailed characteristics of the pollution, lighting, and scene conditions are rarely known.

The generalized approach uses aerosol species extinction efficiencies, with water growth functions, to determine the light extinction coefficient of the aerosol, from its composition and from the relative humidity of the atmosphere. The extinction efficiencies and relative humidity dependence of the aerosol are based upon typical results from the more rigorous analyses mentioned above.

A generalized approach is recommended by IWAQM for Class I area analyses. Under this approach, the concentrations of pollutants (in this case calculated by an air quality model) are used to calculate the extinction coefficient due to these pollutants. This is then compared against the light extinction coefficient of the background air. A constant fractional change in the extinction coefficient produces a similar perceptual change for a scene regardless of baseline conditions. Therefore, under cleaner visibility conditions, relatively less pollution will cause a perceptible change than under more polluted background conditions.

Visibility is an instantaneous phenomenon. When an observer looks at a scene, the view is what is seen at that moment. Many of our measurements and modeling techniques deal with averaged values from one hour and longer. Therefore, some consideration is needed to accommodate this dichotomy.

Visibility Parameters

Visibility is usually characterized by either visual range (*VR*) (the greatest distance that a large dark object can be seen) or by the light-extinction coefficient (b_{ext}) (the attenuation of light per unit distance due to scattering and absorption by gases and particles in the atmosphere) (Sisler,1996). Under certain assumed conditions, these parameters are inversely related to each other by Equation 1.

$$VR(km) = \frac{3.912}{b_{ext}(km^{-1})} \qquad (1)$$

The dimensions of *VR* are length and the dimensions of b_{ext} are 1/length. Visual range is usually expressed in kilometers. The extinction coefficient is sometimes expressed as “inverse kilometers” (km^{-1}) or as “inverse megameters” (Mm^{-1}) (the reciprocal of 1 million meters). If b_{ext} is expressed in Mm^{-1}, the coefficient 3.912 in Equation 1 becomes 3912. The value 3.912 = -ln(0.02), which assumes a two percent contrast

threshold for the viewer. Other researcher have assumed a five percent threshold, which would change the value to 2.995.

A constant fractional change in the extinction coefficient produces a similar perceptual change for a scene regardless of baseline conditions. Using the relationship of a constant fractional change in the extinction coefficient resulting in a similar perceived visual change, an alternate visibility index, the deciview (*dv*) has been defined (Equation 2).

$$dv = 10 \ \ln \frac{b_{ext}(km^{-1})}{0.01(km^{-1})} \qquad (2)$$

This index was specifically designed so that anywhere along its scale, haziness changes that are equally perceptible correspond to the same deciview difference. For example, a 3dv difference caused by a change in air quality should result in about the same perceived change in haziness, whether under clean or highly polluted conditions. This characteristic of the deciview scale requires that the scene being viewed has sufficient sensitive scenic features to detect changes in visibility from the baseline haze level. No one scene is likely to have such scenic features for all conceivable haze levels. However, the nearly infinite variety of scenes available, where hazes are concerned, ensures that many will have the desired characteristic for any haze level (NAPAP report to congress).

Calculating the Extinction Coefficient

Visibility is degraded by light scattered into and out of the line of sight and by light absorbed along the line of sight. Light extinction is the sum of light scattering and absorption, and is usually quantified using the light extinction coefficient (b_{ext}). Using the generalized approach to estimating visibility effects, outlined above, one can calculate the extinction coefficient as the sum of its parts, i.e., $b_{ext} = b_{scat} + b_{abs}$, where b_{scat} and b_{abs} are the light scattering and absorption coefficients. The light scattering and absorption coefficients can be further broken down by their respective components. The scattering coefficient is affected by Rayleigh scattering (b_{Ray}) from air molecules and from particle scattering (b_{sp}); the particles can be natural aerosol or result from air pollutants. The absorption coefficient is affected by gaseous absorption (b_{ag}) and particulate absorption (b_{ap}). Nitrogen dioxide is the only major light-absorbing gas in the lower atmosphere; it generally does not affect hazes, although it can be an important element in a coherent plume assessment. Therefore, only particle absorption is considered in the suggested haze analyses.

Particle scattering, b_{sp}, can be broken down by the contributions of different particulate species. It has been convenient to consider the scattering coefficients of

fine particles ($PM_{2.5}$) (particles with mass mean diameters less than or equal to 2.5 µm) and coarse particles (mass mean diameters greater than 2.5µm but less than or equal to 10µm). The fine particle scattering coefficient can be further defined by the sum of the scattering coefficient due to sulfates (b_{SO4}), nitrates(b_{NO3}), organic aerosols (b_{OC}), and soil (b_{Soil}); the coarse scattering coefficient (b_{Coarse}) is typically not refined any further. Thus the particle scattering coefficient (b_{sp}) can be expressed as in Equation 3.

$$b_{sp} = b_{SO4} + b_{NO3} + b_{OC} + b_{Soil} + b_{Coarse} \tag{3}$$

Each of the particle scattering coefficients can be related to the mass of the components using the relationships in Equation 4.

$$\begin{aligned} b_{SO4} &= 3\ [(NH_4)_2SO_4]\ f(RH) \\ b_{NO3} &= 3\ [NH_4NO_3]\ f(RH) \\ b_{OC} &= 4\ [OC] \\ b_{Soil} &= 1\ [Soil\ Mass] \\ b_{Coarse} &= 0.6\ [Coarse\ Mass] \end{aligned} \tag{4}$$

The quantities in brackets are the masses expressed in µg/m^3. (It is assumed that the forms of the $SO_4^=$ and NO_3^- are ammonium sulfate [$(NH_4)_2SO_4$] and ammonium nitrate [NH_4NO_3].) The numeric coefficients are the dry scattering efficiencies (m^2/g). The term *f(RH)* is the relative humidity adjustment factor. The extinction coefficients are in Mm^{-1}. If the dry scattering efficiencies are divided by 1000 (i.e., 0.003 instead of 3) the resultant extinction coefficients will be in km^{-1}.

Particle absorption (b_{ap}) is primarily due to elemental carbon (soot). For purposes of analyzing the effects of soot on visibility in a modeling analysis, the relationship in Equation 5 should be used. Again, the quantity in brackets is the mass of elemental

$$b_{ap} = 10\ [EC] \tag{5}$$

carbon in µg/m^3 and 10 is the extinction efficiency.

The total atmospheric extinction can be expressed as in Equation 6. To the extent that a source contributes to the formation of some of these constituents, those

$$b_{ext} = b_{SO4} + b_{NO3} + b_{OC} + b_{Soil} + b_{Coarse} + b_{ap} + b_{Ray} \tag{6}$$

contributions can be summed to yield the source's contribution to extinction. This will be discussed in more detail below.

Examination of Equation 4 reveals that the sulfate and nitrate components of the extinction coefficient are dependent upon relative humidity. These aerosols are hygroscopic and the presence of water enhances their scattering efficiency. It is sometimes convenient to consider the sulfate and nitrate components of extinction separately from the remaining components of Equation 6 and to keep the relative humidity adjustment factor (*f(RH)*) separate. Equation 6 can then be rewritten as in Equation 7,

$$b_{ext} = b_{SN}\ f(RH) + b_{dry} \tag{7}$$

where

$$b_{SN} = 3\ [(NH_4)_2SO_4 + NH_4NO_3]$$
$$b_{dry} = b_{OC} + b_{Soil} + b_{Coarse} + b_{ap} + b_{Ray}$$

where b_{SN} is the combined extinction coefficient of sulfate and nitrate, excluding the relative humidity adjustment factor, and b_{dry} is the sum of b_{OC}, b_{Soil}, b_{Coarse}, b_{ap}, and b_{Ray}.

The relative humidity adjustment factor requires some further explanation. The variation of the effect of relative humidity on the extinction efficiency of sulfates and nitrates is shown in Figure 1. As can be seen, the effect of relative humidity on the extinction efficiency of these aerosols is non-linear, and is several times greater at higher relative humidities. These factors are applicable on a short-term basis. If the particulate concentrations are only available over a longer averaging time (i.e., a 24-hour sample or a seasonal average) then the average relative humidity adjustment factor for that time period must be applied, ***not*** the average relative humidity. (Alternately, short-term extinction coefficients (i.e., 1-hour) may be averaged to yield a longer-term average.)

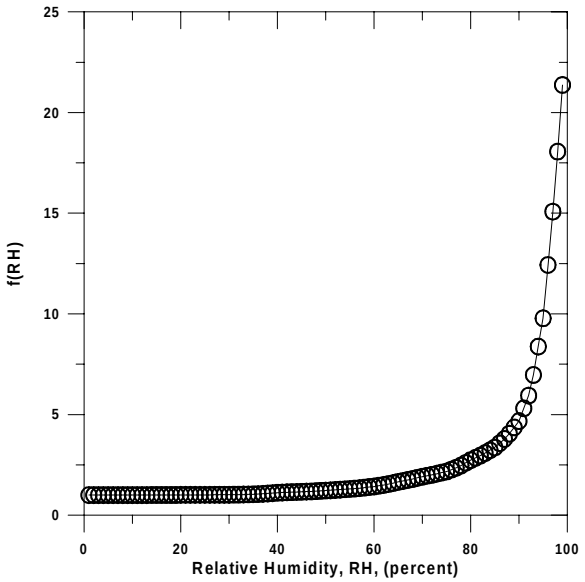


Figure 1. Variation of f(RH) (see Equation 7).

Background visibility conditions

As noted previously, visibility analyses are compared against a background condition. The estimates of background visibility conditions at Class I areas are derived from the IMPROVE (Interagency Monitoring of PRotected Visual Environments) network. There are several methods of obtaining estimates of the background visibility. These include reconstructed extinction from speciated measurements of particulate matter, direct measurement of extinction with a transmissometer, and estimates of extinction from photographs (Malm et al., 1996). Reconstructed extinction is usually used to estimate background conditions, since this can be directly related to pollutant loadings. It should be noted that reconstructed extinction values from the IMPROVE network are based on 24-hour average particulate concentrations. The temporal average at a point is used to represent a short-term spatial average.

The background conditions provided for a Class I visibility analysis will be representative of clean conditions. Changes in visibility are most sensitive under clean conditions. By using clean conditions for all comparisons in a Class I analysis, it ensures that already clean conditions will not be impaired. Additionally, the Clean Air Act states as a national goal that the visibility in Class I areas is to be unimpaired by man-made air pollutants and that any such impairment is to be remedied. To represent clean conditions, the average of the cleanest 20% of the data from IMPROVE, at that site, is generally used. Even the data from the cleanest days usually exhibit some made-made influence. This average of 24-hour values for the 20% cleanest conditions is used as representative of a clean background condition.

Background conditions may be provided using any of the visibility parameters, defined above, although the preferred method is to use the extinction coefficient, with the hygroscopic components and other components dissociated, as in Equation 7. Using the form of Equation 7 allows the effects of relative humidity to be applied consistently to both the background aerosol and the aerosol attributable to a new source. If only one of the other visibility parameters is available, without the dissociation of the hygroscopic components, then that value would be used. However, the relative humidity conditions that represent the average background will likely be different than the condition being analyzed. The usual effect of this is that the relative effect of sulfate and nitrate emissions is overstated under high relative humidity conditions.

Calculating a change in extinction

The modeling techniques outlined in this recommendation will provide ground level concentrations of visibility impairing pollutants. These concentrations are then used to calculate the extinction coefficient due to these pollutants, using the relationships outlined in Equations 4 and 5. The results of this are then compared against the background extinction from Equation 7. The metric used for this comparison is usually the change in deciview (Δdv) from a "clean" background condition. Thus, for a given background extinction, b_{back}, and a source or sources contribution to extinction of b_{source}, Δdv is given by Equation 8.

$$\Delta dv = 10 \ln \frac{b_{back} + b_{source}}{b_{back}} \tag{8}$$

These methods are embodied in the CALPOST program which post-processes the concentrations from the CALPUFF air quality model. However, if another model is used it is necessary to be able to perform these calculations separately. Even if the CALPUFF system is used, it is sometimes more convenient to calculate changes in visibility outside of the post-processor.

Example Problem

This example assumes that a dispersion model has been run and yielded concentrations of $SO_4^=$ and soot (elemental carbon). From these concentrations the analyst wishes to calculate a change in visibility.

First, we will consider the background visibility condition. If the background 24-hour average visibility at the Class I area of interest has a combined sulfate and nitrate extinction coefficient (b_{SN}) of 1.8 Mm^{-1} (neglecting the effects of relative humidity) and an extinction coefficient from the other components (b_{dry}) of 19.6 Mm^{-1}, then the background extinction (b_{back}), expressed in the form of Equation 7 would be:

$$b_{back} = 1.8\ f(RH) + 19.6$$

In a typical analysis, the model will be run for an extended period, such as a month, a season, annually, or for multiple years. This will produce a corresponding number of 24-hour averaging periods, which will each need to be analyzed against the background condition. In our example we are only considering one 24-hour averaging period. For this example we will assume that the sources in the analysis contributed 0.218 µg/m^3 of sulfate ($SO_4^=$) and 0.05 µg/m^3 of soot (elemental carbon). The first step is to convert the mass of $SO_4^=$ to ammonium sulfate ($(NH_4)_2SO_4$), which is accomplished by multiplying by the ratio of the molecular weights of $(NH_4)_2SO_4$ to $SO_4^=$, which is 1.375. This yields a concentration of $(NH_4)_2SO_4$ of 0.30 µg/m^3. This result is then multiplied by the dry scattering efficiency of $(NH_4)_2SO_4$ (which is 3, from Equation 4), yielding an extinction coefficient for the sulfate of 0.9 Mm^{-1}; the relative humidity adjustment has not yet been applied. In this example, our modeling does not require any conversion of the mass of soot, so we need only to multiply the soot concentration (0.05 µg/m^3) by the extinction efficiency of elemental carbon (which is 20, from Equation 5). This yields an extinction coefficient of 1.0 Mm^{-1}. Therefore, following the form of Equation 7, the source contribution would be:

$$b_{source} = 0.9\ f(RH) + 1.0$$

The relative humidity adjustment factor for this averaging period has not yet been applied. Our example is based on a 24-hour average. The representative hourly RH values for this day would need to be obtained. For each hour, the corresponding *f(RH)* must be obtained from Figure 28 (or a corresponding table). These values are then averaged together. Let us assume that for this day the average *f(RH)* is 3.4. With the day-average relative humidity adjustment factor (*f(RH)*) of 3.4, b_{back} would be 25.72 Mm^{-1} (corresponding to a visual range of 152 km from Equation 1) and b_{source} would be 4.06 Mm^{-1}. Using these values in Equation 8 would yield a Δdv of 1.46.

These calculations would be repeated for each 24-hour average concentration in the analysis, using the corresponding day-average *f(RH)*. Background visibility conditions may be given for seasons or months. The corresponding background values should be used. A spread sheet program is suggested if the results are not processed with the CALPOST processor.

Visibility Summary

The following list summarizes the steps necessary for conducting a visibility analysis under this recommendation.

- Consult with the appropriate regulatory agency and with the appropriate FLM
- Run an air quality model which yields ambient concentrations of visibility impairing pollutants
- Obtain data on the background visibility conditions for use in the form of Equation 7, $b_{ext} = b_{SN}f(RH) + b_{dry}$
- Calculate the extinction coefficient for the source or sources being analyzed using Equations 4 and 5.
- Apply appropriate and consistent relative humidity adjustment factors to both the source contribution to light-extinction and the background light-extinction.
- Calculate a change in deciview (Δdv) using equation 8.

3.3 Deposition Calculations

Estimates of atmospheric deposition are obtained by selecting the options in CALPUFF to calculate and output the wet and dry fluxes of the pollutants modeled. The units of the fluxes are in $g/m^2/s$ of the pollutant modeled (i.e., $g/m^2/s$ of HNO_3). Generally AQRV analyses require values of total deposition (background plus modeled impact) to be given in units of kg/ha/yr of an element, such as nitrogen (N) or sulfur (S). Therefore, the modeled deposition flux of each of the oxides of sulfur or nitrogen from CALPUFF must be adjusted for the difference of the molecular weight of their oxides and the element and the various forms must be summed to yield a total deposition of sulfur or nitrogen. This can be accomplished using a multiplier in CALPOST to do all of the conversions. The CALPOST program will produce an average flux (i.e., annual average), therefore, the average value must be multiplied by the number of seconds in an hour and the total number of hours used in the averaging period for the total deposition.

The wet and dry fluxes of SO_2, $SO_4^{=}$, NO_X, HNO_3, and NO_3^- need to be calculated and saved in a CALPUFF run. It is necessary to make a separate CALPOST run of the wet and dry fluxes for each species modeled, normalizing each species by the molecular weight of a common compound or element (usually S or N), converting the units, and adjusting for the total number of averaging periods used in the CALPOST run (i.e., 8760 for 1 year). Then the results of the sulfur CALPOST runs are summed and the results of the nitrogen CALPOST runs are summed to yield a total deposition value for sulfur and nitrogen, respectively. The following table indicates the multipliers to use to correct for molecular weight differences and unit changes, as well as the correction to go from a short-term flux to annual deposition.

Deposition of:	Ratio Mol wt. of Oxidant to S or N	g to kg	m2 to ha	sec to hours	Number of Hours in	Multiplier (a in CALPOST) x N
S from SO_2	0.50000	10^{-3}	10^4	3600	N	1.800000E+04
S from SO_4	0.33333	10^{-3}	10^4	3600	N	1.200000E+04
N from NOX	0.30435	10^{-3}	10^4	3600	N	1.095652E+04
N from HNO3	0.22222	10^{-3}	10^4	3600	N	8.000000E+03
N from NO3	0.22581	10^{-3}	10^4	3600	N	8.129032E+03

For example, if CALPUFF was run for SO_2 and $SO_4^=$, for one year, it would be necessary to run four different CALPOST runs for wet and dry deposition of SO_2 and $SO_4^=$. For the SO_2 runs, the multiplier in CALPOST would be set to $1.8x10^4x8760 = 1.576x10^8$, assuming a non-leap year with 8760 hours and to $1.2x10^4x8760 = 1.0512x10^8$ for the $SO_4^=$ runs. If one was interested in the deposition over the month of January, assuming a run length of 744 hours, one would use 744 in place of the 8760 to calculate the multiplier in CALPOST.

3.4 Assessing Air Quality Related Values - Background

It usually is not possible to assess Air Quality Related Values (AQRVs) in isolation of the existing background stress. To illustrate this point, we consider two examples. The first using a leaf injury model and the second discusses discerning differences in visibility.

Larsen et al., (1983) presented a model of leaf injury, in which leaf injury was seen to be a function of the hourly sulfur-dioxide concentration raised to the 1.845 power times the ozone concentration raised to the 1.271 power. The impact for a series of hours was to be computed as a summation over each hour's computed effect. What should be noted is the fact that the injury was not linear, but was proportional to a power, in this case, greater than 1. We can simplify this to an equation of the form:

$$D = a\ \chi^p$$
$$\chi = b + b'$$

where D = damage, a is some constant, p is a power (like those cited above), χ is the total concentration (or deposition, etc.), which is composed of a background concentration, b, and an additional concentration, b', associated with one or more sources. If p is not equal to 1, then it is not possible to assess the effects of the background concentration, b, separately from the effects associated with one or more sources, b'.

Example: Let p = 2, b = 10 and b' = 1, then D = 121a. If one separately computes the damage as a summation, as D = D(b) + D(b'), the result will underestimate the total damage, as D = 100a + a = 101a.

The deciview, dv change associated with adding some new source's effects onto an existing background haze effect can be computed as:

$$dv = 10 \ln[\frac{(b + b')}{b}]$$

where b is the extinction coefficient associated with the background and b' is the extinction coefficient associated with the additional source or sources. It is worth noting in the above equation that the human perception of a change in visibility is fundamentally a function of the existing background condition. A one dv change is computed whenever the ratio (b+b')/b = 1.11. Or stated in other terms, when b' is 11% of b, a one dV change in the visibility will be computed.

These two examples were provided to illustrate that assessing some Air Quality Related Vales (e.g., as might be related to crop injury, or visibility effects) is fundamentally tied to knowing the current stress (background) being exerted on the system. Assessing the response of a resource (plant health, visibility) is related to the cumulative effects of all the current existing stresses. Whether a model is used to estimate the existing condition, or whether existing monitoring measurements can be used to define the current stress (background), is decided for each case based on available information.

4.0 STUDIES AND FINDINGS

Sections 4.1 through 4.5 provide extended summaries of the investigations conducted prior to the Sixth Modeling Conference. Following the Sixth Modeling Conference, a series of investigations were conducted in response to the comments received, and these results are summarized in Sections 4.6 through 4.9. In Section 4.6, summaries are presented of several investigations in which surface concentration values estimated by the CALPUFF puff dispersion model were compared with tracer field data. These are presented to provide further information, as requested at the Sixth Modeling Conference, for deriving conclusions on the performance of the CALMET/CALPUFF modeling system in characterizing long-range transport. In Section 4.7, a summary is presented in which direct model-to-model comparisons are made between CALPUFF and ISC simulations of point source release dispersion. These are presented to provide evidence on the ability of CALPUFF to replicate the dispersion results of ISC for steady-state meteorological conditions. Some coding deficincies were detected in compariing the steady-state CALPUFF results with ISC, but the primary lessons learned were what differences could be expected due to the fact that puff models treat the sequence of meteorological events ('causality'). This information is valuable since CALPUFF was to be used to simulate all sources (even though for some, the transport may be less than 50 km) in a long-range transport assessment. Section 4.8 summarizes results available towards developing a new screening technique that might be used to see if it is worthwhile or needful to develop a full wind-field puff-dispersioin analysis using the CALMET/ CALPUFF modeling system. It was evident at the Sixth Modeling Conference that use of the ISC plume dispersion model to develop screening estimates of long-range transport impacts was not providing much help. Section 4.9 summarizes studies that have recently been completed of further enhancements and refinements, some of which are implemented in Version 5.0 of the CALMET/CALPUFF modeling system. Not all of these enhancements have been fully tested, but it was felt desirable to summarize that which was known.

4.1 MESOPUFF II Implementation Assessment

A case study was conducted to apply the MESOPUFF II air quality modeling system following IWAQM Phase 1 interim recommendations (U.S. EPA, 1993). This study would identify and summarize the decisions made, would record and summarize the resolution process for these decisions, and would provide a written record of the resources used to complete the effort. The objective was to learn by experience where the difficulties are in the process of conducting such an analysis, and when possible, to provide a means for resolving these difficulties. It was not an objective to provide a meaningful assessment of PSD, NAAQS or AQRV impacts for the Class I areas considered in the study. A complete description of the study results is presented in U.S. EPA (1995a). As part of this study the following tasks were carried out:

- The MESOPUFF II model and associated processors were tested using the example problem intended for Support Center for Regulatory Air Models

bulletin board (SCRAM BBS) distribution. The SCRAM BBS example problem computer files were evaluated and some suggested improvements were implemented.

- A five-year meteorological data set suitable for input to the MESOPUFF II model was developed for a multi-state area surrounding Shenandoah National Park (SNP), including the James River Face (JRF) wilderness area. Demonstration model simulations were performed using three years of the developed five-year meteorological data set for the assessment of visibility, acidic deposition, and PSD increments for a set of real sources in the states surrounding Shenandoah National Park.

- Model simulations were performed to test the sensitivity of concentrations to the distance between sources and receptors using a set of "pseudo" sources placed in successive rings around Shenandoah National Park.

As discussed in the summary report for this project (U.S. EPA, 1995a), on several occasions significant departures were made in conducting this study from that which would be expected if a realistic assessment were to be developed. For instance, the source inventory considered only some of the states surrounding the Shenandoah National Park and the James River Face wilderness area, and thus is incomplete. To conserve resources, the sources were consolidated into ten surrogate sources for the purposes of this study. These departures allowed the emphasis of the project to be focused on a critique of the process and resource needs, which were the primary study objectives.

A realistic assessment, would require that all important sources be modeled (without consolidation). If the modeling objective is to determine PSD impacts, then all relevant sources that consume PSD increment must be considered. If one desires to determine the impact of a single new (or modified) source, then the PSD increment from the new source must be added to all pre-existing PSD sources. It would be possible to model the impacts from a single source and then add those impacts to prior MESOPUFF II results, assuming the prior results were available. If not, it would be necessary to model all relevant PSD sources to assess the total PSD increment consumed.

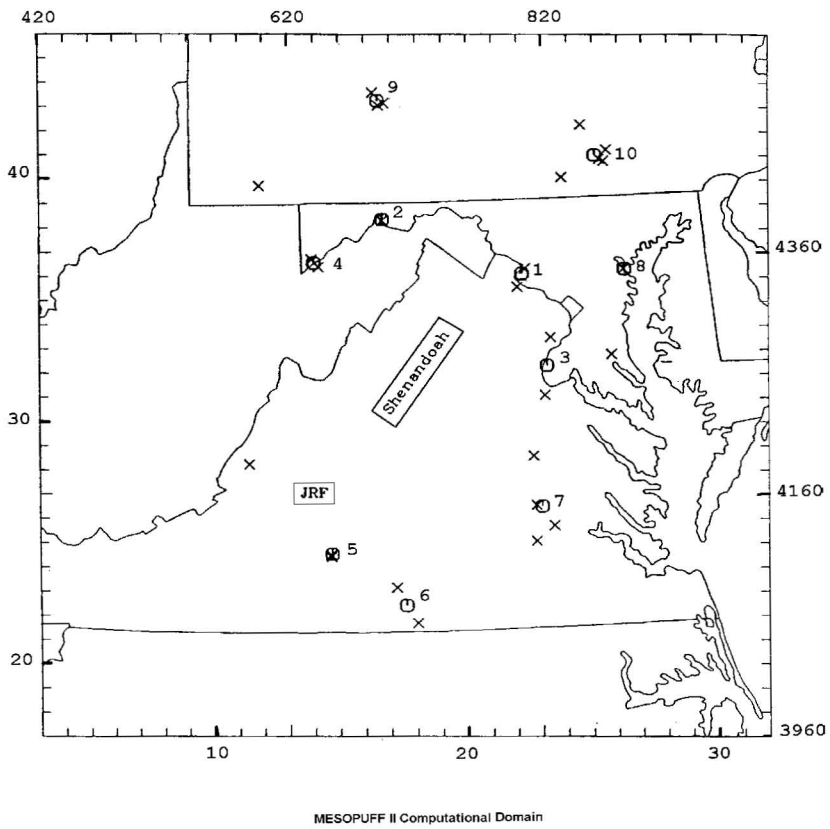


Figure 2. Display of the MESOPUFF II computational domain, showing positions of all PSD sources compiled for the demonstration assessment. Crosses represent all 27 original PSD sources, while circles denote the ten final aggregated sources used for the demonstration analyses. The source characteristics for the ten aggregate sources (numbered) are given in Table 2. One unit along left and bottom axes equals 20 km. Top and right axes are the UTM coordinates in km.

Demonstration Results

In the MESOPUFF II modeling for this project, only one run was performed (for three years) using sources beyond 50 km of Shenandoah National Park. The MESOPUFF II results (for one month) were then added to ISCST2 results to demonstrate the integration process. For the demonstration study, sources were to be located as far as 200 km from SNP. All sources and receptors to be modeled must be contained within the computational domain. Puffs are not tracked after they leave this grid. To avoid underestimating concentrations by immediately losing puffs from near-boundary sources or missing short-term recirculation events at near-boundary receptors, all sources and receptors should be at least 20-50 km from the boundaries of

the computational grid. Provision for a 80 km buffer zone on all sides of this source region yielded a computational domain of 30 by 30 grid points (Figure 2), with a grid spacing of 20 km.

For the demonstration study, existing sources that began operation since the beginning of the PSD program would be modeled. For practical considerations and ease of communications between affected states, the sources were limited to those within EPA Region III, comprising the states of Delaware, Maryland, Pennsylvania, Virginia and West Virginia, and the District of Columbia. Small PSD sources, with emissions of both SO_2 and NO_x less than 5 g/s, were excluded. This resulted in a set of 27 sources (indicated by crosses in Figure 2). To reduce run times the set of 27 sources were consolidated into 10 sources. Table 3 shows the final set of 10 consolidated sources, the facilities that are included in each, and the location and emission parameters. Figure 2 also displays the locations of these ten sources (indicated by circles) in relationship to all 27 original PSD sources.

Table 3. Final condensed set of sources modeled with MESOPUFF II for the demonstration assessment. HS, DS, VS, and TS are the source's stack height, stack diameter, effluent exit velocity, and effluent exit temperature, respectively.

	Sources	UTM X (km)	UTM Y (km)	HS (m)	DS (m)	VSI (m/s)	TS (K)	SO_2 (g/s)	$SO_4^=$ (g/s)	NO_x (g/s)
1	PEPCO II, Patawmack	803.6	4341.0	48	8.77	36.6	557	348.2	15.7	230.4
2	Warrior Run	693.6	4385.0	82	3.75	23.6	398	54.8	2.5	26.0
3	Ogden-Martin, SEO Birch	823.6	4265.0	106	3.24	10.0	372	48.0	2.2	151.9
4	N. Branch, Mettike	639.6	4349.0	76	4.69	21.3	389	112.1	5.0	83.6
5	LG&E Altavista, Multitrade	653.6	4109.0	60	4.44	21.4	407	24.7	1.1	42.6
6	Mecklenburg, Old Dominion	711.6	4067.0	109	7.11	18.6	331	194.6	8.8	425.1
7	Doswell, Cogentrix-Richmond, Cogentrix-Dinwiddie, LG&E Hopewell	819.6	349.6	70	5.35	14.0	352	252.1	11.3	426.4
8	Brandon	885.2	4345.0	187	6.71	27.3	413.	1893.6	85.2	630.8
9	Cambria Cogen, Colver PP, Ebensburg	689.6	683.6	86	5.08	21.3	418	287.8	13.0	155.8
10	P.H. Glalter, Harrisburg, Lancaster, Solar Turbine, York Co.	861.6	4439.0	67	6.60	15.4	438	14.1	0.6	212.3

For this study, PM_{10} increments were calculated as described in the Phase 1 recommendations. Modeled concentrations of sulfate and aerosol nitrate were converted to ammonium sulfate and ammonium nitrate, and summed to estimate PM_{10} increments. The PSD increments were calculated for each receptor, and the highest values within SNP and JRF were identified. Since there are no standards or mandated increments for AQRVs, it was necessary to define AQRV criteria before postprocessing could begin. For visibility, incremental extinction coefficients were computed from 3-hour average modeled sulfate and nitrate concentrations using relative humidity data

and the equation provided in Appendix B of the Phase 1 recommendations. The maximum 3-hour extinction resulting from modeled emissions over all receptors was compared to measured total extinction from the SNP IMPROVE monitoring site. The number (and percentage) of 3-hour periods for which the maximum extinction represents 10 percent or more of the measured extinction for the 90th percentile cleanest day was reported. Deposition impacts were calculated for each receptor for total sulfur (SO_2 plus sulfate, expressed as S) and total nitrogen (NO_x plus HNO_3 plus nitrate, expressed as N). Deposition impacts were expressed as the cumulative annual sum of wet and dry deposition, in units of kg/hectare.

Table 4. PSD and AQRV parameters calculated from MESOPUFF II demonstration assessment.

		Shenandoah NP			James River Face			Allowable Class I Increment
Parameter	Averaging Period	1988	1989	1990	1988	1989	1990	
		PSD Increments						
SO_2	Annual (ug/m3)	0.23	0.32	0.21	0.08	0.10	0.06	2
	24-hour (ug/m3)	3.92	5.03	3.15	1.39	2.93	1.61	5
	3-hour (ug/m3)	16.56	19.62	9.55	5.38	7.35	3.65	25
NO_x	Annual (ug/m3)	0.12	0.15	0.13	0.05	0.07	0.04	2.5
PM_{10}	Annual (ug/m3)	0.08	0.12	0.07	0.05	0.07	0.04	4
	24-hour (ug/m3)	1.24	3.32	1.31	0.85	1.25	1.31	8
		Visibility						
Extinction	3-hour (% of year)	19.9	27.9	22.4	7.3	8.2	6.8	
		Deposition						
Total S	Annual (kg./Ha)	0.38	0.36	0.28	0.11	0.15	0.08	
Total N	Annual (km/Ha)	0.09	0.12	0.07	0.04	0.16	0.03	

Extinction = percent of 3-hour periods for which incremental extinction is greater than 10 percent of clear-day extinction levels.

Table 4 displays a summary of calculations from three years of MESOPUFF II output (1988-1990). Results are given for receptor groups in both SNP and JRF. There is considerable year-to-year variations in all of the simulated impacts, typically of order 20 to 25%. As for concentrations of criteria pollutants, annual averages of SO_2, NO_x, and modeled PM_{10} in both Class I areas were predicted to be small fractions of the total allowable Class I increments for all years modeled. Short-term concentration increments were predicted to approach the allowable Class I increments, particularly at SNP. The second highest 3-hour and 24-hour average SO_2 concentrations approach or exceed the allowable Class I increments, while the second highest 24-hour average modeled PM_{10} is between an eighth and one-half the allowable limit. Also note, that

whereas the summer 1988 was characterized by widespread high pollution levels throughout the eastern U.S. (particularly for ozone), all modeled concentration, extinction, and deposition predictions were distinctly higher during 1989 than during the other two modeled years at both Class I areas.

The extinction measure reported in Table 4 corresponds to the percent of each year in which calculated sulfate plus nitrate concentrations lead to extinction levels more than 10 percent above the defined "clean" background levels for SNP. According to these calculations, it is predicted that secondary particulate matter from the PSD sources modeled in this analysis lead to such conditions between 20 and 28 percent of the year for SNP, and about 7 to 8 percent of the year at JRF. At SNP, maximum 3-hour extinction for the years 1988, 1989, and 1990, were 0.0507, 0.3348, and 0.1345 km^{-1}, respectively. Using a simple standard estimation procedure for clear-sky visual range (3.0 divided by extinction in km^{-1}), the extinction levels computed for SNP translate to minimum visual ranges of 59, 9, and 22 km, respectively, for each year modeled. The maximum extinction levels are quite high when one considers that these estimates were calculated solely as a result of particulate matter generated by these emission sources alone, and that other SO_2 and NO_x sources, and natural and anthropogenic sources of organics and dust, were not taken into account.

Source-Receptor Separation Distance Sensitivity Study

A set of 24 MESOPUFF II simulations were performed with sources at varying distances from Shenandoah National Park (SNP) to provide some insight into the relationship between distance from SNP and potential PSD and AQRV impacts (U.S. EPA, 1995a). Four months of one year (representing each season of a year) were modeled under six different source scenarios. Each source scenario included a number of identical hypothetical point sources placed on a ring at a constant distance from the "spine" of the SNP. The source rings were established at 50, 100, 125, 150, 175, and 200 km from the spine (Figure 3).

The distribution of hypothetical point sources around each ring was determined such that the linear density of sources was held as constant as possible. The emission rates and source emission characteristics were set to be similar to those listed in Table 3. The emission rate and stack parameters used for the hypothetical sources are summarized in Table 5. The stack parameters are average values from the PSD source data in Table 3. Emission rates of primary sulfate were specified at 3 percent of SO_2 rates, with an additional 1.5 factor to account for the larger sulfate molecular weight. Source characteristics of each ring are summarized in Table 6, and the locations of the sources are shown in Figure 3.

Table 5. Emission rates and stack parameters for the idealized sources.	
Stack Parameters	Value for Idealized Sources
SO_2 Emission Rate (g/s)	181.0
SO_4 Emission Rate (g/s)	8.1
NO_x Emission Rate (g/s)	135.0
Stack Height Im)	81.0
Stack Diameter (m)	3.97
Stack Gas Exit Velocity (m/s)	20.7
Stack Gas Exit Temperature (K)	425.0

A total of 24 MESOPUFF II runs were made, corresponding to six distances for each of the four months. MESOPUFF II output for the ring source analysis consisted of 3-hour average concentrations, and wet and dry fluxes of all species. 24-hour averages and monthly averages were produced for NO_x, nitric acid, sulfate ($SO_4^=$), nitrate (NO_3^-) and modeled PM_{10}, $SO_4^=$ and NO_3^- concentrations output by MESOPUFF II were multiplied by factors of 1.38 and 1.29 to convert to ammonium sulfate, $(NH_4)_2SO_4$, and ammonium nitrate, NH_4NO_3, respectively (these conversions are discussed further in Section 3). Following the Phase I recommendations, the sum of ammonium sulfate and ammonium nitrate was reported as modeled PM_{10}. Total sulfur deposition was calculated by summing wet and dry deposition fluxes for SO_2 and $SO_4^=$ over the month. Conversion factors were applied to convert SO_2 and $SO_4^=$ to a sulfur basis, and to convert 3-hour average fluxes to 3-hour cumulative deposition. Total nitrogen deposition was calculated by summing wet and dry deposition fluxes for NO_x, HNO_3, and NO_3^- over each month. Conversion factors were applied to convert NO_x, HNO_3, and NO_3^- to a nitrogen basis, and to convert 3-hour average fluxes to 3-hour cumulative deposition. (For further discussion of the computations of total S and N deposition, see Section 3.3). An important AQRV associated with PM_{10} is visibility. MESOFILE was not capable of producing visibility estimates as outlined in the Phase I recommendations, where extinction is a function of relative humidity. Thus, visibility impacts were not assessed for the ring source analysis.

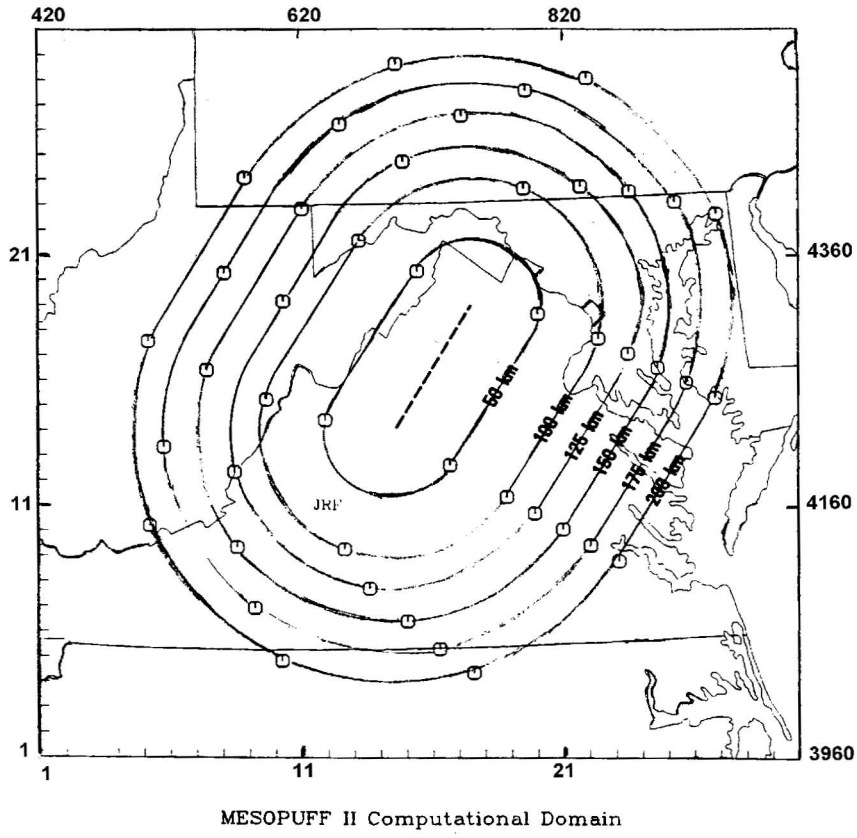


Figure 3. MESOPUFF II computation domain for ring source analyses, showing the location of the ring sources. One unit along left and bottom axes equals 20 km. Top and right axes are the UTM coordinates in km.

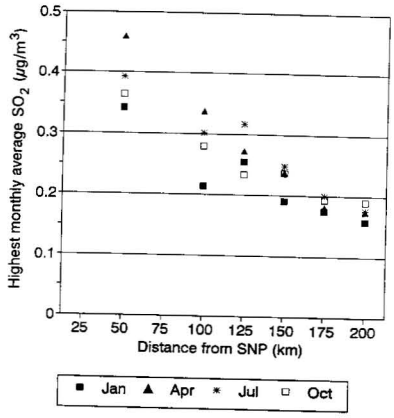
Figure 4a shows the results obtained for the monthly average SO_2 concentration for each of the four months as a function of source distance from SNP. The nearly linear decrease as a function of distance from SNP seen for these results is typical of that seen in the highest 24-hour average SO_2 results. As might be expected for a primary pollutant, the highest impacts occur for the 50-km source ring. The highest monthly average concentration is 0.45 µg/m^3, and decreases by a little over a factor of 2 for sources located on the 200 km ring. The maximum 3-hour and 24-hour SO_2 concentrations were also for the sources on the 50 km ring and were 20 µg/m^3 and 2.8 µg/m^3, respectively. The computed maximum 3-hour SO_2 concentration for sources on the 50 km ring is close to the allowable 3-hour increment of 25 µg/m^3. The computed maximum 24-hour SO_2 concentration for sources on the 50 km ring is slightly more than half the allowable Class I PSD increment of 5 µg/m^3.

Table 6. Source ring characteristics.				
			Total Emissions (g/s)	
Distance from SNP (km)	Number of Sources	Distance Between Sources (km)	SO_2	NO_x
50	4	138	724	540
100	6	144	1086	810
125	7	146	1267	945
150	8	148	1448	1080
175	9	149	1629	1215
200	10	150	1810	1350

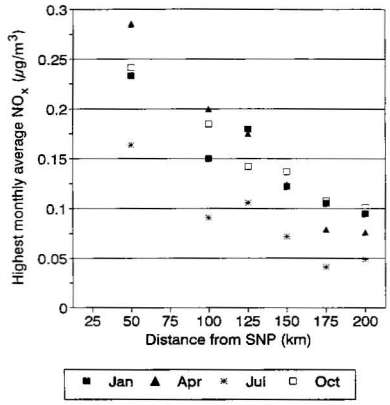
Figure 4b shows the highest monthly average concentrations for NO_x. (Plots of shorter-term NO_x concentrations were not prepared because there are no short-term PSD standards for NO_x.) Comparison of Figure 4a to Figure 4b for monthly average SO_2 illustrates the faster rate of chemical decay for NO_x. For sources on the 50 km ring, NO_x concentrations are generally on the order of 60 percent of the SO_2 concentration for January, April, and October, reflecting the ratio of the emission strengths of SO_2 and NO_x in the ring source input files. NO_x concentrations at 50 km are 40 percent of SO_2 concentrations for July because NO_x reacts much more rapidly than SO_2. For sources on the 200 km ring, NO_x concentrations are on the order of 50 percent of the SO_2 concentration for January, April, and October, and 30 percent of SO_2 concentrations for July. The highest monthly average NO_x concentration was slightly less than 0.3 $\mu g/m^3$, or about 11 percent of the allowable increment of 2.5 $\mu g/m^3$ for NO_x annual average in Class I areas. The annual average will be lower than the highest monthly average. Thus, much greater NO_x source strengths than those used in this analysis would be needed for NO_x concentrations to approach the allowable increment.

Figure 4c presents the highest monthly average modeled PM_{10} concentrations as a function of source distance from SNP. These impacts show a completely different pattern than SO_2 or NO_x, in that there is no clear decrease with source ring distance. This pattern is expected as, unlike SO_2 or NO_x, sulfate and nitrate are actively being formed during transport downwind. The seasonal effect is very pronounced for the monthly average modeled PM_{10}, with July concentrations more than twice those in January, and April and October falling somewhere between the two. Modeled sulfate and nitrate

(A)



(B)



(C)

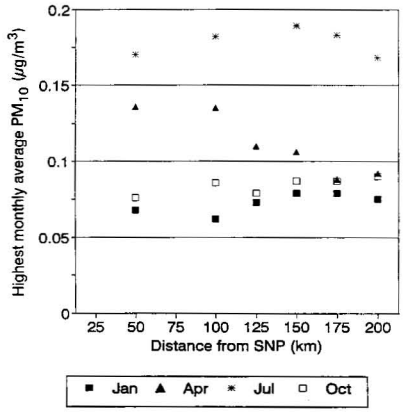


Figure 4. Highest monthly concentrations of (A) SO_2, (B) NO_x, and (C) PM_{10} (µg/m3) from ring sources for January, April, July and October, 1988.

concentrations were nearly equal for all months but July. This is contrary to measured PM_{10} data for SNP and other locations in the eastern U.S., where sulfate concentrations are typically three times as large as nitrate concentrations. Two factors are likely to be responsible for this apparent inconsistency. The high background ammonia concentration of 10 ppb used as a default value in the MESOPUFF II analysis will result in an overestimate of aerosol nitrate concentrations. However, the lack of a parameterization of rapid in-cloud sulfate formation in MESOPUFF II may lead to an underestimate of sulfate concentrations.

The highest monthly total S deposition of nearly 0.05 kg/hectare occurred for July for the 50 km ring. Modeled S deposition decreased with source distance from SNP, although the decreasing trend was very weak for October. For all sources, the highest S deposition occurred in July, and the lowest in January. Dry SO_2 deposition accounted for most of the modeled S deposition in all months. Deposition of $SO_4^=$ was small for all months except July. The main reason for this is that most of the total sulfur remained in the form SO_2 at all distances modeled. Wet deposition shows greater random variability than dry deposition. This makes sense, as wet deposition requires both a puff and precipitation to be present at the same time at a given receptor. Thus, trends in wet deposition with source distance are somewhat obscured by random variability.

The highest monthly total N deposition of 0.013 kg/hectare occurred for the 50 km ring for July. Modeled N deposition decreased slowly with source distance from SNP. For all sources, the highest N deposition occurred in July, and the lowest in January. Total N deposition was less than half the modeled total S deposition for all months and distances. MESOPUFF II assumes zero wet deposition for NO_x. The majority of modeled N deposition in July is due to dry deposition of HNO_3. In the other months, NO_x dry deposition is important, and NO_3^- deposition can be important as well. Considering the high solubility of HNO_3, the modeled wet deposition of HNO_3 appears surprisingly low.

The equilibrium between HNO_3 and NO_3^- affects the results presented here, both for the modeled PM_{10} concentrations and the nitrogen deposition. The ring source analysis utilized the default value for background ammonia of 10 ppb. This value is likely to be too high, especially for winter. When ammonia concentrations are high, the nitrate equilibrium favors the formation of aerosol nitrate. As a result, modeled aerosol nitrate values may be too high. For N deposition, it is less clear what the effect of high background ammonia would be. Dry deposition is faster for HNO_3 than it is for NO_3^-, but wet deposition is faster for NO_3^-. Snow is assumed in MESOPUFF II to scavenge particles, but not gases. If background ammonia is high, NO_3^- deposition will be overestimated and HNO_3 deposition will be underestimated. The net effect on N deposition may be small.

4.2 Revisions to CALMET and CALPUFF

In the course of completing the Phase 1 recommendations, IWAQM had become aware of the CALMET/CALPUFF modeling system (Scire et al., 1990ab), which was actively under development. Building from lessons learned from the MESOPAC/MESOPUFF II modeling system, the CALMET/CALPUFF modeling system was a Lagrangian puff model designed to include: 1) the capability to treat time-varying point and area sources, 2) suitability for modeling domains from tens of meters to hundreds of kilometers from a source, 3) predictions for averaging times ranging from one-hour to one year, 4) applicability to inert pollutants and those subject to linear removal and chemical conversion mechanisms, and 5) applicability for rough or complex terrain situations. The CALMET meteorological processor was designed to be compatible with both CALPUFF and a photochemical grid model, called CALGRID (Scire et al., 1989). Even though the current focus of IWAQM was on puff model simulations, the Phase 3 work was anticipated to include grid modeling. Hence the compatibility of CALMET to a grid model was considered advantageous.

There were two areas where IWAQM felt further enhancements were needed. With a view towards allowing one model to be used for all sources (which might include sources-receptor distances of less than 50 km), the first area for enhancement was to include within CALPUFF dispersion additional algorithms, so that CALPUFF simulation results would be consistent with ISC and CTDMPLUS (Perry et al., 1989) modeling results for steady-state meteorological conditions. The ISC plume dispersion model is recommended in the *Guideline* for use in gently-rolling terrain, and the CTDMPLUS plume dispersion model is recommend in the *Guideline* for use in complex terrain where plume impaction on elevated isolated terrain features is likely. Both ISC and CTDMPLUS are limited to source-receptor distances of less than 50 km. The IWAQM has concluded that one of the most challenging issues for long-range transport is the characterization of the time-varying three-dimensional wind field. Therefore, the second area for enhancement to the CALMET/CALPUFF modeling system was to include provisions within CALMET to allow use of mesoscale meteorological modeling results created using data assimilation techniques, for example Stauffer and Seaman (1989) and Stauffer et al., (1990).

At the time of the Sixth Modeling Conference, there were only preliminary sensitivity testing results to show that the modifications to CALPUFF would be successful in replicating ISC. There were no comparison results available showing consistency between CALPUFF and CTDMPLUS. Comparisons of CALPUFF with ISC are presented in Section 4.7. In following discussion, we summarize the modifications that were made to CALMET to expand its use to long-range transport applications.

The wind field module in CALMET is based on the Diagnostic Wind Model (DWM). In anticipation of using CALMET and CALPUFF for long-range transport distances, a series of modifications were made (U.S. EPA, 1995b). These included options to use a spatially variable initial guess field based on observations or results

from coarse-grid mesoscale meteorological modeling analyses, optional use of Lambert conformal coordinates for sources and receptors versus Universal Transverse Mercator (UTM) Cartesian coordinates, and (as mentioned before) provisions to allow processing of mesoscale meteorological modeling results created using data assimilation techniques.

The DWM in CALMET uses a two step procedure in developing the final wind fields. An initial guess field is developed based on a domain-average wind profile, and this domain-average profile of winds is adjusted for terrain effects and divergence minimization to produce a “Step 1" wind field. The second step in the processing of the wind field is the introduction of the observational data into the terrain-adjusted Step 1 wind field. As originally configured, the initial guess domain-average profile was constant over the domain. For long-range transport analyses, it is easily conceivable that terrain features (such as a ridge, or a deeply cut river gorge that turns sharply within the computational domain) would invalidate the appropriateness of using an initial guess wind profile that is everywhere the same over the domain (i.e., homogeneous). To address this, options were added to CALMET that allow spatially variable winds as an initial guess field. The spatially variable winds are computed using an inverse-distance interpolation from the available wind profile observations. The provision to allow use of a Lambert conformal projection versus a flat Cartesian mapping of receptors and sources was perfunctory, but necessary, in anticipation of analyses that might include transport distances where the curvature of the earth might become a significant factor in the analyses (say computational domains larger than 200 km by 200 km).

The adaptations needed to allow use of meteorological wind fields as analyzed by sophisticated mesoscale meteorological models (hereafter referred to as *FDDA-MM data*) involved more than simply providing a new data input option. Four Dimensional Data Assimilation (FDDA) and the development of *FDDA-MM* data are discussed further in Section 4.4. The representativeness of the fine-scale observations (which can be viewed as point-value observations) as compared with winds derived from *FDDA-MM* analyses (which can be viewed as grid-average observations) was expected to depend on such factors as the height above the surface, subgrid-scale terrain variations, and the ratio of the input *FDDA-MM* data grid size to the output grid size of the CALMET analyses. For example, the *FDDA-MM* results having a grid spacing of 80-km will not reflect potentially important local features of the surface flow field induced by terrain variations (e.g., in vicinity of the Shenandoah National Park or the Columbia river gorge) which can not be resolved by a grid resolution of 80 km. On the other hand, the point-value observations in such areas do not necessarily represent larger-scale flow fields as well as the *FDDA-MM* data fields. Therefore, IWAQM investigated development of a weighting factor based on the subgrid-scale terrain variations, that could be employed to blend the *FDDA-MM* data fields into the network of available surface and upper air observations. The developmental work to define the blending weights is described in the summary project report U.S. EPA (1995b). The

detailed description of how to compute the weights is provided in the current CALMET user's guide.

The decision as to where to introduce the *FDDA-MM* winds in the CALMET processing involves judgment. Basically, the finer the grid resolution used in developing the *FDDA-MM* winds the more reasonable it is to bring these data directly in as observations in developing the Step 2 winds. The coarser the grid resolution used in developing the *FDDA-MM* winds, the more reasonable it is to bring in these data to initialize the Step 1 analyses, and allow the diagnostic wind model of CALMET to develop the local terrain effects.

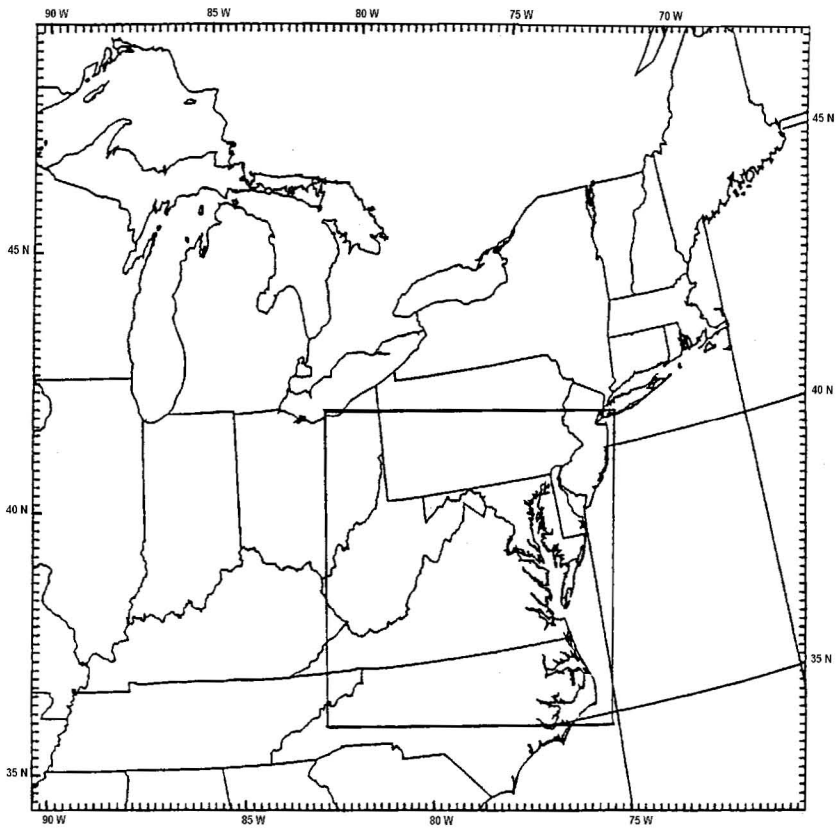


Figure 5. The MM4 domains for the 54-km grid (outer box) and the 18-km grid (inner box).

Table 7. Summary of statistical comparisons of wind fields.

	54-km Results		18-km Results	
	R^2	RMSE	R^2	RMSE
80-km MM4 Interpolated	0.961	0.992	0.958	0.949
CALMET-L Observations only	0.789	2.211	0.858	1.774
CALMET-S Observations only	0.542	3.220	0.814	2.039
CALMET-L MM4 as initial guess field	0.926	1.378	0.920	1.328
CALMET-S MM4 as initial guess field	0.932	1.316	0.922	1.300
CALMET-L MM4 as Step 1 field	0.962	0.992	0.959	0.932
CALMET-S MM4 as Step 1 field	0.962	0.993	0.959	0.938
CALMET-L MM4 as observations	0.960	1.020	0.952	1.011
CALMET-S MM4 as observations	0.959	1.021	0.952	1.011

R^2 = correlation coefficient, and RMSE = root mean squared error.
L = large radius of influence settings, and S = small radius of influence settings.
R^2 and RMSE are computed on a concatenation of the time series of the east-west (u) and north-south (v) components of the wind (each of length N) into one time series (of length 2N).

The radii used were defined as:

	Small	Large
R1	50 km	500 km
R2	100 km	1000 km
Rmax1	100 km	500 km
Rmax2	200 km	1000 km
Rmax3	1000 km	1000 km

where R1, R2 = the distances at which the Step 1 wind and observations have equal weight in the surface layer (R1) and the upper layers (R2), Rmax1, Rmax2 = the maximum radius of influence of observations in the surface (Rmax1) and upper layers (Rmax2), and Rmax3 = the over-water radius of influence.

To investigate the effectiveness of the terrain weights developed, the CALMET diagnostic wind field model was used to analyze two episodes, one summer episode (August 1-6, 1988) and one winter episode (December 3-10, 1988). The summer episode was characterized by light wind, stagnating conditions. The winter episode was characterized as an active period that included the passage of a front and low-pressure system through the domain. Penn State Mesoscale Meteorological (MM4) results were available employing four dimensional data assimilation (Stauffer and Seaman, 1989) for both episodes, for three different grid resolutions, 18-, 54- and 80-km. Figure 5 depicts the domains over which comparisons were made of CALMET simulated wind fields, developed for comparison with the MM4 54-km winds (outer box in Figure 5) and with the MM4 18-km winds (inner box in Figure 5). The CALMET winds were developed using the MM4 80-km winds as input (at various stages in the CALMET processing),

and CALMET winds were developed using only the hourly surface weather observations and twice-daily upper air observations from the National Weather Service.

Table 7 summarizes the comparison results obtained by using the available 80-km MM4 winds in various ways with CALMET to develop either 54- or 18-km gridded wind fields. As a further comparison, the hourly 80-km MM4 winds were linearly interpolated directly to the 54- or 18-km grid resolution. In general, the introduction of the 80-km MM4 winds improves the ability of CALMET to reproduce the reference 54- and 18-km MM4 wind fields. Slightly better agreement was achieved when the 80-km MM4 winds were brought in after the diagnostic terrain adjustment procedures (i.e., as the Step 1 wind fields or as "observations"). This is conjectured to occur due to the fact that 1) the 80-km MM4 are already close to the 54- and 18-km MM4 results, and 2) the CALMET diagnostic adjustments may duplicate terrain effects that were already accounted for in the development of the 80-km MM4 winds. The similarity of the interpolated 80-km MM4 winds to the 54- and 18-km MM4 winds (as evidenced by the close agreement achieved by simple linear interpolation) suggest that there might not be significant new terrain effects between the 80-, 54-, and 18-km scales for this region of the United States.

4.3 Trajectory Comparisons

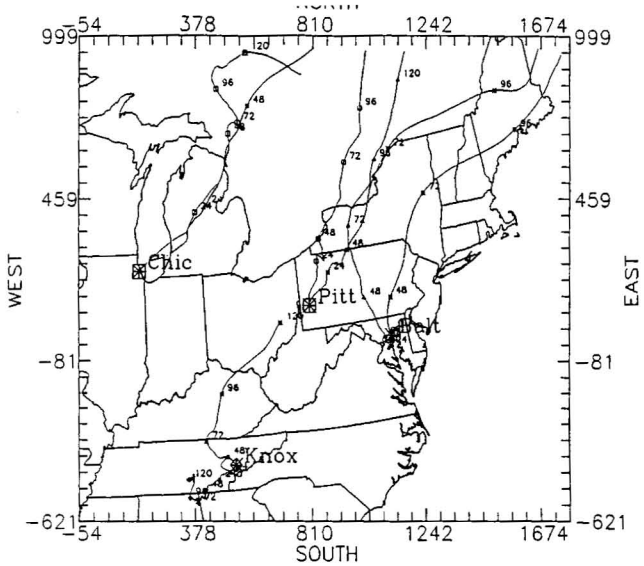
As discussed in the previous section, modifications were made to CALMET in anticipation of using CALMET and CALPUFF for long-range transport distances (U.S. EPA, 1995b). It was anticipated that use of *FDDA-MM* winds would improve CALPUFF's characterization of trajectories of dispersing pollutants. To investigate this, two trajectory studies were conducted: 1) a numerical simulation study, and 2) a comparison with regional-scale observations of trajectories.

<u>Numerical simulation study</u>

Trajectories were computed from four release locations at three levels (10 m, 200 m, and 400 m) for each of the wind fields discussed in Section 4.2 for the summer episode (U.S. EPA, 1995b). Trajectories were generated at each location every 4, 6 and 12 hours from the beginning of the simulation, for up to 24 hours before the end of the simulation. A statistical analysis was conducted on the trajectories to assess the effect of the different wind fields.

Figures 6a and 6b show the trajectories at an elevation of 10 m on the 54 km grid for each of the four locations. The trajectories developed using the MM4 54 km gridded meteorology directly are shown in both figures with small "x's." The trajectories developed using the CALMET generated 54 km winds are shown in both figures with

(A)



(B)

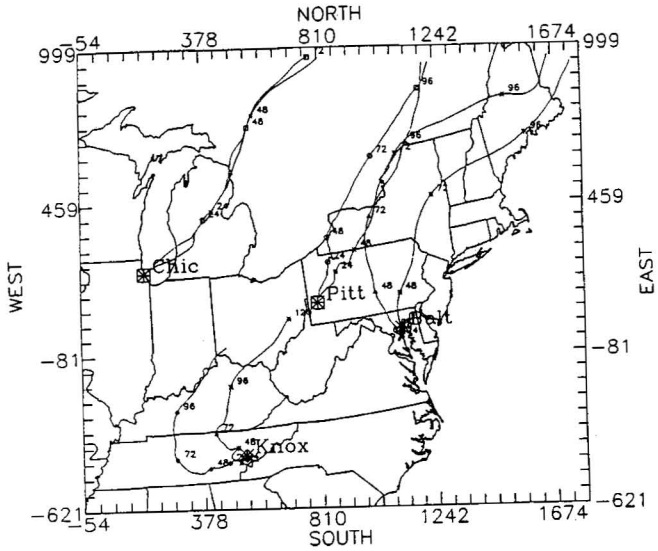


Figure 6. Trajectories at 10 m on the 54 km grid produced by CALMET (A) using the large radius of influence and observations only, and (B) using the large radius of influence and introducing the MM4 80 km winds in the Step 1 initial guess. CALMET results are shown with “o” and trajectories developed directly from MM4 54 km winds are shown with “x”. The starting date was August 1, 1988 at 7 AM. The small numbers indicate hours after release.

small “o’s.” Figure 6a illustrates the results obtained by CALMET with observations only, and Figure 6b illustrates the results obtained by CALMET by introducing the MM4

80 km winds in the development of the Step 1 initial guess wind fields. The most striking differences between the two figures is for the trajectory developed from the Knoxville release location. The CALMET winds (based on observation only) show a light southwest flow, whereas the winds resulting from introducing 80 km MM4 winds to CALMET show the corrent movement towards the north and northeast.

Trajectory statistics were computed from each release time for each site and three levels. In general, the introduction of the 80 km MM4 winds into CALMET to develop either 54 km or 18 km gridded wind fields significantly improved the comparisons with the trajectories developed from the 54 km and 18 km MM4 wind fields directly, versus using only the routine hourly weather observations and twice-daily upper air observations as input to CALMET. There was a slight difference to be seen in using a large or small radius of influence in developing the trajectories with CALMET when only observations were input to CALMET. When the MM4 data are used as input to CALMET, the choice of the radius of influence appears statistically to have no effect on the trajectory comparisons.

CAPTEX comparisons

One of the objectives of the CAPTEX comparisons (Irwin et al., 1996) was to assess whether use of mesoscale dynamic wind fields developed using Four-Dimensional Data Assimilation (FDDA), exhibiting improved spatial and temporal resolution versus typical mesoscale wind fields determined diagnostically from the available hourly surface and twice-daily upper air observations, would improve the quality of the characterization of the transport and dispersion. Results were generated for CAPTEX releases 3, 5 and 7.

The Cross-APpalachian Tracer EXperiment (CAPTEX) is a unique series of tracer releases, which besides testing a particular tracer technology, was conducted for the purpose of providing data to evaluate and improve computer models of pollutant dispersion and to provide insight into the mechanisms involved in long-range transport and dispersion (Ferber et al., 1986). A three-hour ground-level release of perfluoromonomethylcyclohexan (C_7H_{14}, PMCH) was made five times near Dayton, Ohio and twice from near Sudbury, Ontario when winds were expected to transport the tracer over the ground-level sampling network. Samplers were operated at 86 sites in Ohio, Pennsylvania, New Jersey, New York, New England and southern Canada at distances from 300 to 1100 km from the release site. Air concentrations were collected for 3- and 6-hour durations for several days following each release.

Meteorological data available for use in developing the CAPTEX wind fields consisted of 122 National Weather Service (NWS) surface locations reporting hourly and 13 upper-air locations reporting twice-daily (0000 GMT and 1200 GMT) throughout the region. Furthermore, mesoscale wind fields developed using FDDA were available on an 80-km grid. Three wind field models were used to obtain a gridded field of meteorological data with a horizontal resolution of 18-km: MESOPAC II, CALMET, and

CALMET using the mesoscale wind fields as STEP-1 inputs. In the discussion to follow, the latter modeled wind field is referred to as CALMET/MM4.

Version 8 of the Penn State/NCAR Mesoscale Model - Generation 4 (MM4) was used to develop profiles of atmospheric wind, temperature, and moisture. The MM4 is a primitive equation, mesoscale, hydrostatic Eulerian modeling system of the atmosphere (Anthes et al., 1987). The vertical layers are terrain following. FDDA is incorporated as Newtonian nudging by adding to the general momentum and thermodynamic equation a "Force-Restore" term, to effectively nudge the numerical solution towards the observed data (Stauffer and Seaman, 1989; Stauffer et al., 1990). Nudging was applied for the east-west and north-south wind components, temperature and mixing ratio at all levels, except for temperature at the surface and at levels aloft within the lowest 6 layers of the analyses (top of sixth layer is typically 1500m). The horizontal grid spacing of the MM4 simulation was 80 km in both dimensions, with a grid array size of 84 by 55 centered on 90°W longitude and 40°N latitude to cover the domain of the CAPTEX releases.

MESOPUFF II was driven by each of the modeled wind fields to produce a set of three simulations of ground-level concentrations for each of the three CAPTEX releases (9 simulations in all). CALPUFF was driven by two of the modeled wind fields, CALMET and CALMET/MM4, to produce a set of two simulations of ground-level concentrations for each of the three CAPTEX releases (6 simulations in all).

In both the MESOPUFF II and CALPUFF simulations, chemical transformations, dry deposition and wet removal were not modeled because PMCH was assumed to be inert and non-depositing. No attempts were made to optimize the choice of model options within CALPUFF, such as the dispersion coefficients, mode of incorporation of MM4 data, and meteorological vertical layer structure. In effect, CALPUFF was run in a mode designed to make it most like MESOPUFF II, in order that the effects of different wind fields and transport characterization could be identified. MESOPUFF II and CALPUFF differ in the way transport winds are computed for each puff. MESOPUFF II uses a two-layer wind field, the lower layer for the transport of puffs within the mixed layer, and an upper layer field for puffs above the mixing height. For a surface release, as in CAPTEX, MESOPUFF II will always use the lower layer (mixed-layer averaged) wind field. CALPUFF internally computes for each sampling step, a transport wind averaged over the depth of the puff from the multi-layer winds provided to it from CALMET. As the puff grows in the vertical, the depth through which the wind is averaged is increased.

The distance from the nearest to furthest receptor was approximately 800 km and there where 86 receptor locations. The average distance between the receptors was roughly 86 km = $[(800)^2/86]^{1/2}$, which meant that typically there were 4 to 6 receptors with nonzero concentration values for analysis for the shorter travel times (300 to 600 km transport) and from 8 to 16 receptors with nonzero concentration values for analysis for the larger travel times (600 to 900 km transport). This suggests that the

maximum concentration was likely not well characterized and is uncertain both in the observations and in the simulations.

For each 6-hour period, the centroid position was computed for the observed and simulated tracer puff as it was transported downwind over time. The results for each release are shown in Figure 7. It was concluded that the simulated trajectories are sensitive to the manner in which the wind field is characterized, but are insensitive to the model employed. This can be seen by the fact that the simulated trajectories are nearly identical for MESOPUFF and CALPUFF when the models have the same input wind fields.

Ratios were formed by dividing the simulated and observed maximum concentration values for each six-hour period. There was no noticeable trend seen as a function of travel time (hours after release), but clearly there was a tendency to overestimate the maximum concentration value by roughly a factor of 3.7. To further investigate the tendency to overestimate the surface concentration maxima, ratios were formed by dividing the simulated and observed lateral dispersion (as determined from the second moment of the concentration values about the centroid positions) for each six-hour period. There was no apparent trend in the ratio values with travel time following release, however there was a clear trend to underestimate the horizontal extent of the tracer puff for each six-hour period. There were only slight differences seen for the different wind fields employed. The overall geometric average was 0.54 and the geometric standard deviation was 1.81. If the only difficulty or “bias” in the simulation was to underestimate the horizontal extent of the puffs, the effect on the simulated maximum concentration values would be proportional to the inverse square of the bias in the horizontal dispersion, which would be $3.43 = (1/0.54)^2$. It is concluded that the underestimation seen in the simulated horizontal dispersion is able to explain the overestimates seen in the simulated maximum concentration values. The large scatter seen in concentration and lateral dispersion ratio values in part may relate to the stochastic nature of atmospheric dispersion, but also is traceable to poor definition of the maximum concentration values and lateral dispersion.

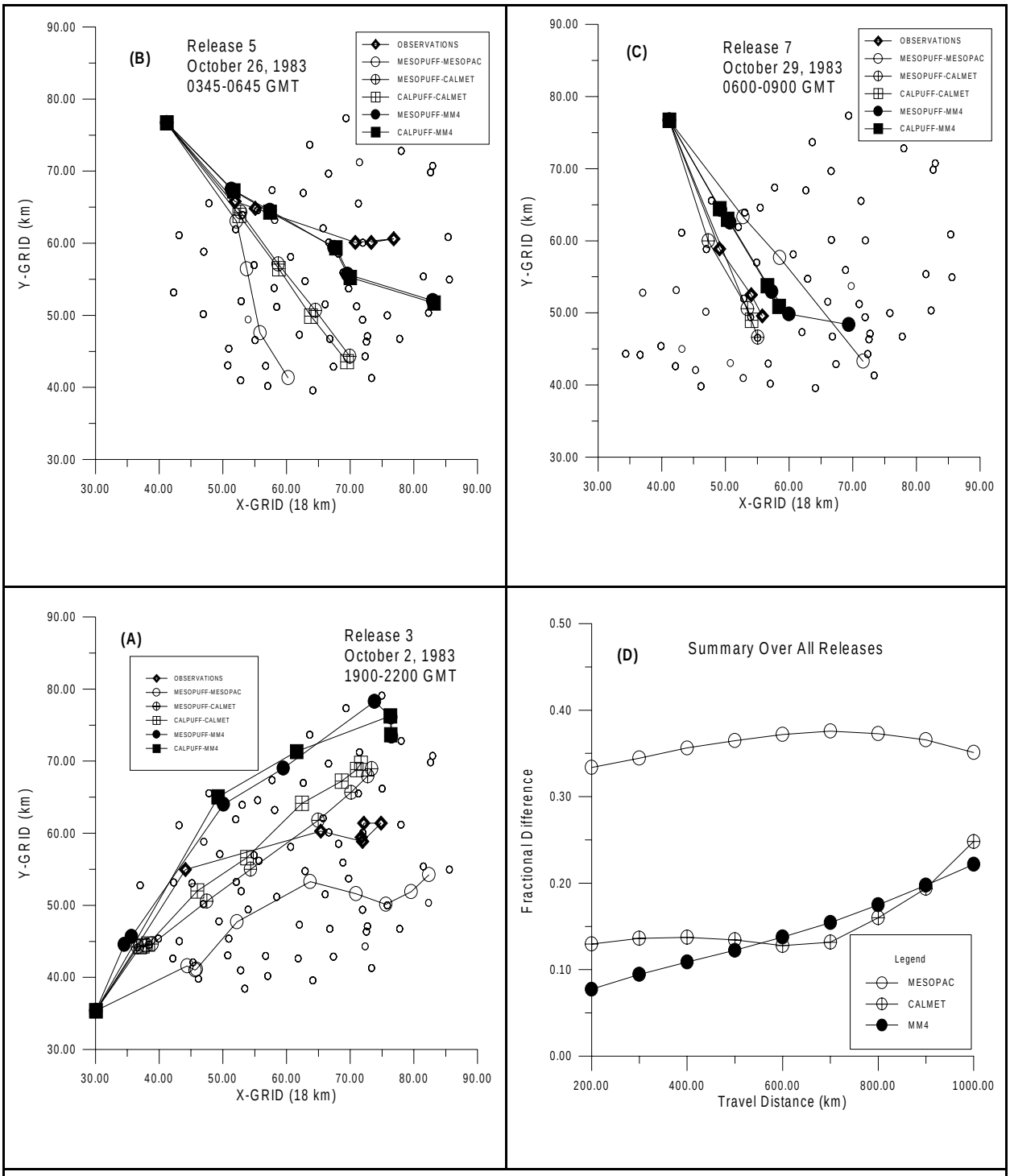


Figure 7. Summary of trajectory results for each of the releases are shown in parts (a), (b) and (c). In part (d) is shown the fractional difference computed between the observed and simulated trajectories, summarized over all releases for each of the three wind fields. The open smaller circles indicate sampling locations. The X and Y coordinates have been specified in terms of the meteorological grid, which had an 18-km size.

The purpose of this investigation was to assess whether different methods of characterizing the wind fields affect the performance of the simulated trajectory. The comparison results presented were conducted with simplified puff dispersion model assumptions, hence the model-to-model differences were minimized. The results shown in Figure 7 suggest a noticeable improvement in the puff simulation results of the centroid trajectory when mesoscale dynamic wind fields developed using FDDA were used to characterize the time and space varying wind field, versus using mesoscale wind fields determined diagnostically from the available hourly surface and twice-daily upper air observations. The favorable comparison of the CALMET wind field results with the MM4 results is influenced by Release 3 results, where CALMET happened to well characterize the average transport direction. The trajectory simulations for Releases 5 and 7 derived using MM4 winds are as good or better than the results obtained with CALMET wind fields derived solely from routine National Weather Service observations. It was concluded that use of MM4 is preferred and that both CALMET and MM4 wind fields provide better simulations of the trajectories than MESOPAC wind fields.

The analysis of the concentration maxima and lateral dispersion values suggest that the simulation assumptions employed in these results consistently underestimate the horizontal extent of the tracer puff as it is transported downwind. The centroid maximum surface concentration was found to be correspondingly overestimated and relatively insensitive to the mesoscale wind characterization. In these simulations, no provisions were made to address delayed shear enhancement of the dispersion as described by Moran and Pielke (1994) and Shi et al. (1990). Inclusion of some sort of puff splitting is obviously warranted, but the computational demands are not trivial if one is attempting to develop an operational model for routine use. Furthermore, in those cases where the puff model dynamics have been enhanced, for example Draxler (1987) and Davis et al. (1986), there was a tendency to underestimate the surface maximum concentrations.

4.4 Constructing *FDDA-MM* Data Sets Assessment

To foster interest in the use of mesoscale meteorological (MM) data processed using Four Dimensional Data Assimilation (FDDA) in routine air pollution modeling assessments and to learn what problems might be associated with such a project, IWAQM sponsored the development of a one-year meteorological data set for 1990 that spans the contiguous United States, southern Canada and northern Mexico. Hourly profiles of wind, temperature and moisture were provided at 23 levels in the atmosphere on an 80-km gird. The Penn State mesoscale meteorological model (MM4) with FDDA was used in developing these data. The horizontal grid spacing of the MM4 simulation was 80 km in both dimensions, with a grid array size of 85 by 56 centered on 90 W longitude and 40 N latitude to cover most of the North American continent and adjacent oceanic areas (Bullock, 1993). The model simulation variables from the outer 2 columns and rows of grid points were not included in the published data set to avoid the boundary effects typical of fixed-grid numerical models. The

domain of the model's vertical coordinate system extended from the earth's surface to the 100 millibar pressure level (approximately 15 km above sea level). The 15-level structure provides height-resolved information similar to that routinely obtained by the National Weather Service at 12-hour intervals from approximately 80 rawinsonde balloon sounding locations across North America. However, the data set obtained from the MM4 simulation provides synthetic soundings at 1-hour intervals for 4080 model grid-point locations, or about 600 times more information than is available from routine observational networks. The 1990 data set contains over 20 billion bytes of information.

The annual data set was developed from the MM4 output of 80 separate simulations. Each simulation was 5 days in length with a 12-hour overlap with chronologically adjacent simulations. This 12-hour overlap was used to allow a model "spin-up" so each simulation's hour 12 conditions would match the previous simulation's ending conditions without the detrimental effects of model initialization. The first 6 hours of each simulation were not used in the definition of the final data set. Hour 7 thru 11 results were blended with the previous simulation results with a time-linear weighting function to produce temporally continuous fields in the final data set. Beginning at hour 12, the simulation results were copied directly in the production of the annual data set. Differences between adjacent simulations for these overlap periods were monitored and no significant discontinuities were detected. At hour 12, the differences were often zero at the floating-point numerical precision of the CRAY Y/MP at EPA's National Environmental Supercomputing Center where the 80 MM4 simulations were performed. Each of these simulations required about 2.5 hours of CPU time to compute on the Cray Y/MP. The MM4 output files were then transferred to a DEC 3500 AXP workstation where the data were chronologically blended and chained and various QA checks were performed. The final product was then re-partitioned into 36 sequential files of about 600 Mbytes each. Three files were produced for each month, the first containing days 1 thru 10, the second containing days 11-20, and the third containing day 21 through the end of each month. These files were then processed by the National Climagic Data Center to produce a 12 Compact Diskette data set (NCDC, 1995).

The science of mesoscale analysis using data assimilation is rapidly developing. Major advancements have been occurring every several months during the period from 1995 through 1997. There are various research groups who have active development programs investigating mesoscale meteorological modeling employing data assimilation, e.g., Pielke et al., (1997), Turner and DeToro, (1998).

A major obstacle is access to these data. The 1990 MM4 data set in a compressed format, and providing only profiles of wind, temperature and moisture, requires 12 Compact Diskettes. An operational means for gaining easy access to comprehensive mesoscale meteorological data sets, as alluded to here, has yet to be developed.

4.5 Regional Approach

Federal and State modelers have struggled with the issues related to Class I area analyses and have found their resolutions to be elusive. Currently the consensus opinion within IWAQM is that air quality impact assessements for Class I areas are fundamentally different from local-scale assessements, typically associated with Class II assessments and State Implementation Plans (SIP's). Unfortunately, the Federal Agencies have attempted to implement the assessment of Class I impacts as if the assessment is similar to that associated with Class II and SIP impacts. This has lead to a significant mis-match between the analysis process and the inherent needs of a Class I impact assessment.

Local-scale assessments require that analyses be performed within a domain on the order of 50 km or less and centered on the source (the domain changes from permit to permit). Given the small domain, Class II analyses lend themselves to individual state implementation. Class I analyses, on the other hand, are centered on specific land areas. Therefore, the modeling domain does not change from permit to permit. Furthermore, these analyses involve a modeling domain on the order of hundreds of km, thus requiring multi-state coordination. Additionally, Class I area analyses for AQRV's may require estimating the deposition of secondary pollutants and their impact on visibility. Finally, the affirmative responsibilities of the FLM's inherantly adds to the coordination difficulties.

As an alternative to the current permit-by-permit practice, Class I air quality modeling assessments could be designed for each Class I area (or cluster of Class I areas). The cornerstone of this approach is an up-front comprehensive increment and AQRV analysis of the area. We envision an "initialization" study being accomplished outside the context of a permit application. An up-front study is preferred since many of the decisions which need to be made (e.g., inventory, AQRV's criteria, etc.) are specific to the Class I area, not the applicant's source. Further, it avoids having these decisions colored by the negotiations which occur for a single source. If desired, the "initialization" can involve technical experts from private and public groups. Finally (and perhaps most importantly), it provides future applicants with up-front information needed for planning and assurance of what is expected for the given situation.

In large part, the emissions inventory and meteorological data which are developed during the initializing process remain fixed in subsequent analyses. Therefore, once "initialization" is complete, each additional new source need only determine its additive contribution; as such, increment and AQRV's are directly tracked. This approach has the benefit of removing the burden, from each applicant, of developing an emissions inventory specific for their application. Updates may be necessary to account for changes in actual emissions from other sources. Within this approach, provisions can be made for updating the initial analysis under certain circumstances. For instance, a re-initialization analyses could result from any one of

the following: 1) periodic State audit as contemplated by the PSD regulations, 2) by choice of the permit applicant, or 3) as the scientific understanding changes. Once the system is "re-initialized", new meteorological data and grids may result.

4.5.1 A Regional Approach to Implementing a Class I Area Assessments

The following outline presents a conceptual approach how the air quality modeling could be accomplished for Class I areas. This approach was designed to provide a framework in which many of the issues could be resolved.

I. **INITIALIZING ANALYSIS**: Use the recommendations of the Interagency Workgroup on Air Quality Modeling (IWAQM) to initialize each Class I area outside the context of a permit application.

- A. Preprocess a fixed 5 year data base. All subsequent analyses will use this data set. That is, the meteorological grid will be fixed for all future analyses.
- B. Define both the computational and receptor grids. These grids are also fixed for all future analyses (unless a reanalysis warrants changes).
- C. Decide on the measures to be used in the Air Quality Related Values (AQRV's) analyses, and determine the significance (*de minimis*) criteria for the AQRV's (this should be done specific to the Class I area)
- D. Develop an Inventory:
  1. Source inventory for PSD increment analyses.
  2. Source inventory for AQRV analyses.
- E. Run IWAQM recommended approach to produce appropriate concentration/impact fields.
- F. Archive these fields for use by future Prevention of Significant Deterioration (PSD) applicants.

II. **INITIALIZATION STUDY PARTICIPANTS**: The initialization work should be a cooperative effort among the FLM for the area and the EPA regions and states who have or could have sources which affect the Class I area. The initialization study participants could include technical experts from industry and academia.

III. **PERMITTING**:

- A. The State within which the Class I area resides could be the ultimate caretaker of all data bases[1]. The data bases would include the meteorological data, the computation and receptor grid definitions, the Class I area specific emissions inventories, the various topographical and other data and the concentration/impact fields.

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[1] An issue yet to be resolved is developing an effective means to assist those States faced with assessing impacts on Class I areas not within their respective borders. Will coordination problems arise between States on roles and responsibilities?

B. Using the data provided, an applicant need only determine its own incremental impacts. These impacts will then be added to the archived concentration/impact fields for comparison against appropriate increments and AQRV's.

IV. **DATABASE UPDATES**: It is envisioned that re-initialization analyses could result from the following:

A. Periodic state audit as contemplated by the PSD regulations.
B. By choice of the permit applicant. An applicant will be permitted to use a more recent 5 year set of meteorological data with the requirement that they perform a complete re-initialization analysis. Such an analysis would update the comprehensive data base for future analyses.
C. As scientific understanding changes.

4.6 Comparisons of CALPUFF with Tracer Field Data

There are very few intensive tracer field experiments available for investigating model simulations of mesoscale transport and dispersion. The IWAQM is aware that there are several other expriments for which the CALMET/CALPUFF modeling system has not been exercised (mostly in Europe). The results that are summarized here represent those that IWAQM was aware of and for which the data could be obtained.

4.6.1 1975 Savannah River Laboratory Tracer Study

In this study (U.S. EPA, 1998a), concentration estimates from the CALPUFF dispersion model were compared to observed tracer concentrations from a short-term field experiment conducted at the Savannah River Laboratory (SRL) in South Carolina on December 10, 1975 (U.S. DOE, 1978). This experiment was designed to examine long-range transport of inert tracer materials to demonstrate the feasibility of using other tracers as alternatives to the more commonly used SF_6. Several tracers were released for a short duration (3-4 hours) and the resulting plume concentrations were recorded at an array of monitors downwind from the source.

For the CALMET/CALPUFF simulations, a meteorological grid extending from 32° N to 34° N latitude and from 80° W to 82° W longitude was used. Figure 8 shows the region of the SRL field experiment. The SRL facility is near the west edge of the domain and the sampling monitors are located along Interstate 95. A 24-by-24 horizontal grid with a 10-kilometer resolution was used for the SRL modeling. To adequately characterize the vertical structure of the atmosphere, six layers were defined: surface-20, 20-50, 50-100, 100-500, 500-2000, and 2000-3300 meters.

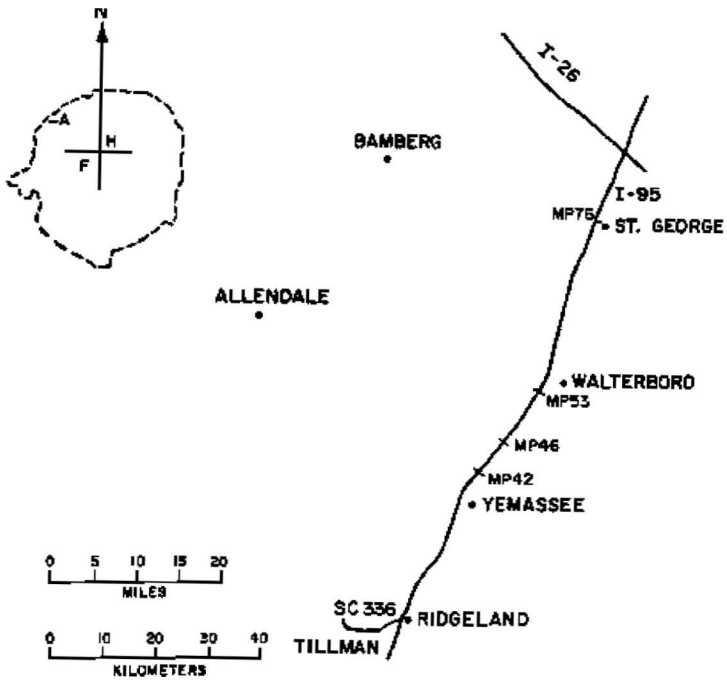

Figure 8. Savannah River Laboratory field experiment site.

The CALMET preprocessor utilizes National Weather Service (NWS) meteorological data and on-site data to produce temporally and spatially varying three dimensional wind fields for CALPUFF. Only NWS data were used for this effort and were extracted from two compact disc (CD) data sets (see Appendix C). The first was the *Solar and Meteorological Surface Observation Network* (SAMSON) compact discs, which were used to obtain the hourly surface observations. The following surface stations were used:

Georgia:	Athens, Atlanta, Augusta, Macon, Savannah
North Carolina:	Asheville, Charlotte, Greensboro, Raleigh-Durham, Wilmington
South Carolina:	Charleston, Columbia, Greer-Spartanburg

Twice daily soundings came from the second set of compact discs, the *Radiosonde Data for North America*. The following stations were used:

Georgia:	Athens, Waycross
South Carolina:	Charleston
North Carolina:	Greensboro, Cape Hatteras

The geophysical parameters were derived from geographical information system (GIS) land-use categories. Terrain and land-use data were available on the CALMET, CALPUFF, and CALPOST Modeling System (version 1.0) CD (hereafter referred to as the CALPUFF CD, see Appendix C). The terrain and GIS land-use data on the CALPUFF CD were used to define gridded land-use data for each field experiment. These data are defined with a resolution of 1/6° latitude and 1/4° longitude.

SF_6 and two heavy methanes were released. For this analysis, the SF_6 tracer emission rates were used. The source parameters for this analysis were, a release height of 62 m, with 154 kg of SF_6 tracer released over a 4 hour period (10.69 g/s) with no buoyant plume rise.

The distance to the monitoring arc was approximately 100 kilometers. The monitors were located along I-95 (Figure 8) from MP76 on I-95 near St. George south to Hwy 336 west of Tillman, SC and along SC 336. The monitors subtended an arc of about 70°. Receptors for modeling were placed along an arc every 1/4° degree from MP76 to MP22 near Ridgeland, resulting in 261 receptor locations. The distance between receptors was about 450 meters.

Two separate CALPUFF model runs were made: 1) using Pasquill-Gifford (PG) dispersion parameters, and 2) using dispersion coefficients from internally-calculated σ_v and σ_w from the micrometeorological variables calculated in CALMET (hereafter referred to as similarity dispersion). The central maximum concentration is estimated from a Gaussian fit to the modeled and observed data (Cmax) and computed from the crosswind integrated concentration (CWIC) and the lateral dispersion, σ_y, as Cmax = CWIC/($\sqrt{2\pi}$ σ_y). The CWIC was computed by trapezoidal integration. The program that computed these measures utilized only those values that were 1% or greater of the maximum.

The observed concentrations are the cumulative concentration from bag samples located along Interstate 95 from about St. George south to Ridgeland (Figure 9). Background concentration was estimated to be 0.5 ppt (DOE, 1978). The tracer release started at 10:25 Local Standard Time (LST) and continued until 14:25 LST. The bag samplers were started at different times, ranging from about 10:40 to 12:30 LST, and the duration of the sampling ranged from 7.0 to 7.5 hours. Since the release started at 10:25 LST, it seems likely that sampling at the monitors would have begun prior to the arrival of the plume. The arrival time of the modeled plume was the hour ending at 13:00 LST for both PG and similarity dispersion. The simulated plume required seven hours to pass the arc with the PG dispersion coefficients, but only six hours with similarity dispersion coefficients. Therefore, seven-hour-average modeled and observed concentrations were computed for comparison with the measurements. Since the first monitors were turned on prior to 11:00 LST and only cumulative concentration is reported for the observed data, the simulated concentrations were summed over the seven-hour period from 11:00 LST through 1800 LST.

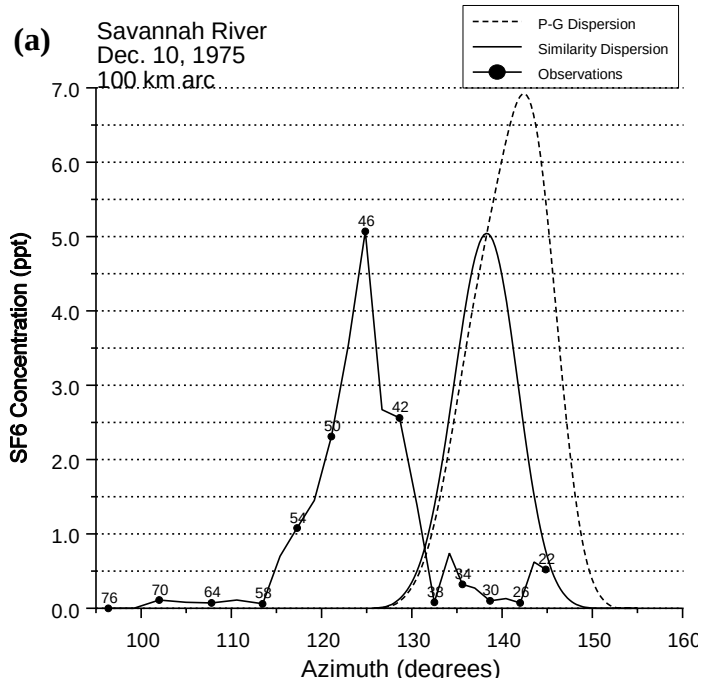

Figure 9. Simulated and observed seven-hour average concentration values along sampling arc for the Savannah River Laboratory December 10, 1975 tracer field experiment.

Figure 9 shows the plots of the concentration estimates at the receptors (continuous curves) and the observed concentrations at the receptors (labeled points). The modeled peaks are 10° to 20° further to the south than the observed peak. It appears that the CALMET meteorology derived using routine NWS was not able to characterize this initial difference in wind direction sufficiently to transport the plume more toward the north.

Clearly, there is general agreement in the shape and magnitude of the distributions. Note that there are two local maxima in the observations near 135° and 145°. The winds were more northerly shortly after the release and may have resulted in the observed local peaks (DOE, 1978) that were not captured in the modeled meteorology. The observed lateral dispersion is 50-100% larger than the modeled dispersion due to these local peaks. If these two secondary peaks are omitted from the analysis, then the statistical measures of the simulated plumes are in better agreement with the measures of the observed plume. Without these secondary peaks, the fitted central maximum to the observations increases by 37% to 3.8 ppt (modeled: PG 7.2 ppt and Similarity 5.1 ppt), The observed computed lateral dispersion is reduced by 33% to 7.77 kilometers (modeled: PG 6.9 km and Similarity 5.0 km). The observed CWIC is reduced only slightly to 0.732 ppt-m (modeled: PG 1.29 ppt-m and Similarity 0.8 ppt-m).

With only one realization for comparison, general conclusions regarding model performance are not possible. But the simulation results are in reasonable accord and do not suggest there are severe problems in the modeling system. It is encouraging that the correspondence is as close as it is given that only routine NWS observations were employed in developing the meteorological fields.

4.6.2 1977 Idaho FallsTracer Study

CALPUFF dispersion modeling results (Irwin, 1997) were compared with data obtained following a single 3-hour late afternoon tracer release, lasting from 1240 to 1540 Mountain Standard Time (MST), conducted on April 19, 1977 near Idaho Falls, Idaho. The tracer release results (Clements, 1979) were obtained as a consequence of an investigation into the feasibility of using certain perfluorocarbons and heavy methanes as alternative tracers in place of sulfur hexafluoride (SF_6). Hence, although the results have found use for testing alternative characterizations of dispersion and transport, this was not a primary purpose in the original design of the investigation. Draxler (1979) included this experiment in an assessment of the effects of alternative methods of processing wind data for characterization of the mesoscale trajectory and dispersion. He concluded that a network of wind observations having a spacing on the order of 25 kilometers might be needed to simulate mesoscale transport associated with variable-flow situations, and that spacing of order 100 kilometers might prove adequate for stationary and homogeneous flow situations.

The design for meteorological data collection and sampling locations relative to the release location is shown in Figure 10. Since locations of towers and sites were extracted from data volume figures, the relative positions are likely accurate but the absolute positions are no better than 0.5 km. The receptor arcs at 48 and 90 km downwind from the release are shown in Figure 10. Meteorological data were available from eleven sites providing hourly-averaged winds; four sites providing hourly-averaged winds and temperatures, three sites providing hourly pibal observations of winds aloft (CFA, MTV, DBS). Two of the pibal sites (CFA and DBS) also provided hourly-averaged winds and temperatures. Hourly rawindsonde observations were taken at about 600 m northwest of the release location. The meteorological masts ranged in height above ground with two at 6.1 m, eleven at 15.2 m, three at 22.8 m, and two at 30 m. The pibal observations taken at Billings, Montana (well past the farthest sampling arc downwind) were not used in this investigation. The skies were clear of clouds and no precipitation occurred during the experiment. The National Weather Service observations taken at Pocatello, Idaho (approximately 75 km southeast of the release location) were included to provide station pressure (required input for CALMET).

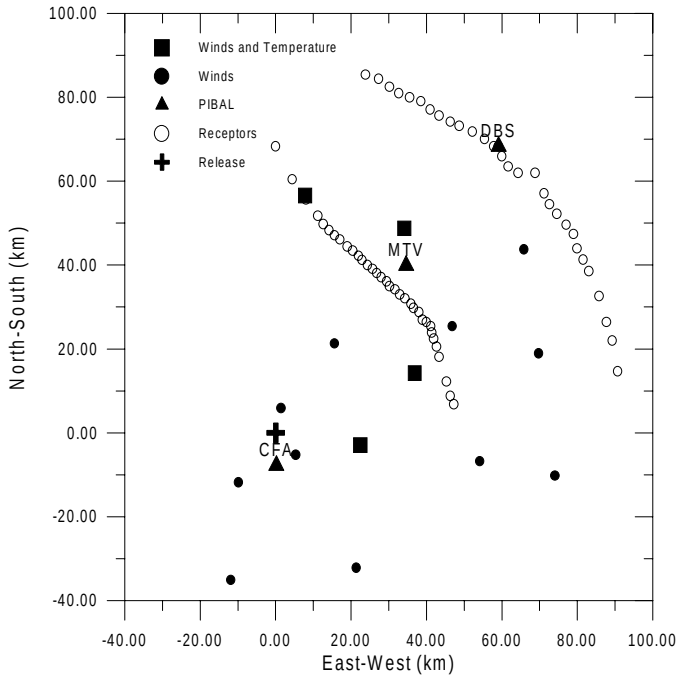

Figure 10. The Idaho tracer experiment sampling arcs and meteorological data collection network. The sampling arcs at 48 km and 90 km are shown. The receptor arc at 3.2 km downwind of the release is omitted for clarity.

To estimate the effects of drainage flow on the near-surface wind field, gridded values of land-use and terrain heights are needed. The land-use data are used as surrogates for typical values of surface roughness, albedo, soil heat flux, anthropogenic heat flux and leaf area index. These surface parameters are used in estimating the surface energy balance. For this analysis, U.S. Geological Service land-use and terrain height data were extracted from data bases included in U.S. EPA (1996). The basic grid size for these data is approximately 900 m. They were processed into a 20 by 20 grid with a grid resolution of 10 km. Default values, as defined in U.S. EPA (1996), for the surface parameters to be associated with the land-use data were used. The southwest corner of this grid was approximately 50 km southwest of the release. The area depicted in Figure 10 is fairly flat, but the terrain sharply increases in height to the west and north of the area depicted. The dominant land-use was rangeland; and the surface roughness was estimated based on land-use to be on the order of 10 centimeters.

Hourly-averaged winds and temperature were available from midnight April 18 through midnight April 19. To mitigate the effects of not having surface data beyond midnight of April 19, the surface meteorological tower data were duplicated to form two

24-hour periods, having identical meteorology. The assumption being made is that conditions were steady-state. The pibal and rawindsonde data, which were available from 0700 MST to 1900 MST, were treated in a similar manner. CALMET assumes all upper-air observations are from rawindsondes, and thus expects upper-air observations to provide winds, dry-bulb temperature and pressure with height. CALMET interpolates in height for missing data values at intermediate heights in an observation, but CALMET will not extrapolate upper air data. Thus observations are rejected that fail to reach the user-prescribed top of the modeling domain (3300 m for this analysis), or have missing data values at the surface. To make use of the hourly pibal observed winds, temperature and pressure values were added by linearly interpolating in time and height between available rawindsonde observations, which were available every 1 to 3 hours. The pibal wind directions were consistent with those from the one rawindsonde, but the wind speeds were generally less in magnitude.

A purpose of this investigation was to assess the effects of having different amounts of meteorological data for use in the development of the time varying field of meteorological data. For this purpose four separate runs were made: Case 1 using all available upper-air and surface mast observations, Case 2 using all surface mast observations but only the one on-site rawindsonde upper-air observation, Case 3 using only the CFA wind and temperature observations with the one on-site rawindsonde upper-air observations, and Case 4 using only the CFA wind and temperature observations with all upper-air observations. In Cases 1 and 2, all the on-site hourly wind and temperature data are employed but different amounts of upper-air observations are used. In Cases 3 and 4, hourly winds and temperatures taken close to the release are used with different amounts of upper-air observations. For all the CALMET simulations, winds and temperatures were computed for six layers in the vertical, the midpoints of which were: 10 m, 35 m, 75 m, 300 m, 1250 m, and 2650 m.

The winds at CFA were higher than those generally seen throughout the network. Hence in Cases 1 and 2 when all the on-site winds were employed the low-level winds were lower than when only CFA data were used. In Cases 1 and 2, the afternoon stability was Pasquill category B/C (Monin Obukhov lengths of order -30 m). As a consequence of higher winds in Cases 3 and 4, the surface friction velocities were higher, and the Monin Obukhov lengths were larger (in magnitude), thus closer to neutral stability. The afternoon mixing heights are similar regardless of data used. This results because the “upper-air” temperatures all have a common source, namely the rawindsonde observations taken 600 m northwest of the release. The nighttime mixing heights are mostly a function of the magnitude of the friction velocity. Hence, where estimated friction velocities were largest and differ most among the various processing methods, differences were seen in the nighttime mixing height values.

Each of the four analyses of meteorology was used to produce two CALPUFF simulations of ground-level concentrations for each of the three sampling arcs. In the first simulation, the dispersion was described using Pasquill-Gifford dispersion parameters. In the second simulation, the dispersion was described using dispersion

parameters suggested by Draxler (1976), which require values of the standard deviation of the vertical and lateral wind fluctuations (referred to hereafter as “similarity dispersion”). The wind fluctuation standard deviations estimated within CALMET are primarily dependent on the surface friction velocity. The surface friction velocity is a strong function of stability (largest during unstable conditions), roughness length and wind speed (increases as roughness length or wind speed increase).

For each sampling step, CALPUFF internally computes a transport wind averaged over the depth of the puff from the multi-layer winds provided to it from CALMET. As a surface release puff grows in the vertical, the depth through which the wind is averaged increases. The SF_6 tracer emission was reported to be steady at 25.37 g/s over the three hour period, and was simulated within CALPUFF as a 3-hour point-source release at 10-m starting at 1300 MST. The release height was set at the midpoint of the lowest CALMET layer, to insure that the internally computed standard deviations of lateral and vertical velocity fluctuations (for use in the similarity dispersion parameter characterizations) at the specified release height, were in accord with the wind speed used by CALPUFF for the lowest layer.

For each 6-hour period, the second moment (lateral dispersion, σ_y) of SF_6 concentration values about its centroid position along the arc was computed. The crosswind integrated concentration, CWIC, was computed by trapezoidal integration. By assuming the concentration profile along the arc is Gaussian, the central maximum, Cmax, was computed as, $Cmax = CWIC/(\sqrt{2\pi}\ \sigma_y)$.

A goal of this investigation was to assess the sensitivity of the modeling results to different treatments of processing the meteorology, as well as to assess the performance of CALPUFF in characterizing dispersion for transport distances beyond 50 km. Figure 11 depicts the observed SF_6 concentrations with the simulation results where all the surface and upper-air observations were used to generate the hourly wind fields. For the observed values, there were from 14 to 17 receptors along each arc with valid data for analysis. For analysis of the simulation results, receptors were spaced at each arc distance at 2 degree intervals, over the 90 degree sector northeast of the

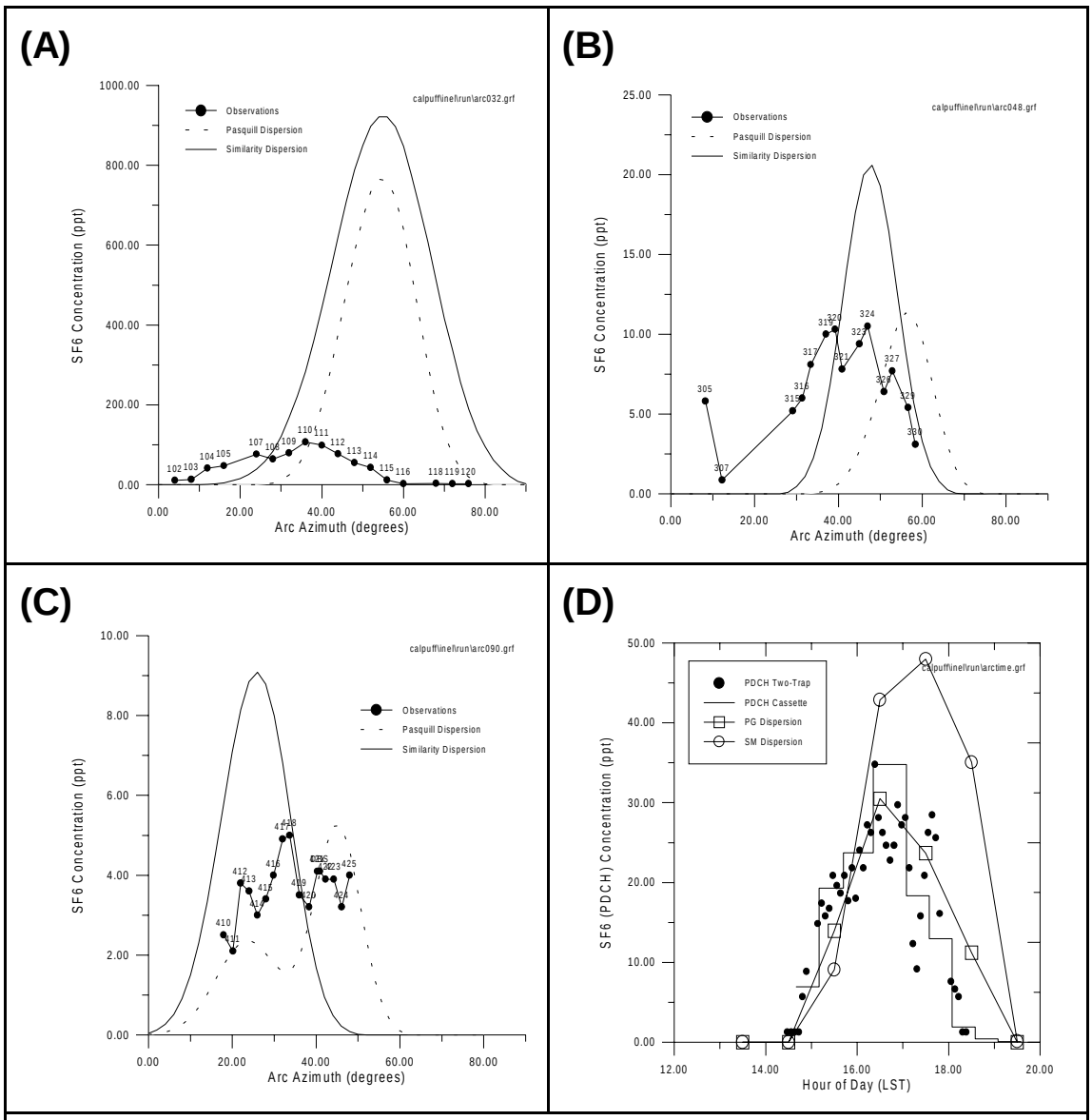

Figure 11. Six-hour average SF_6 concentration values observed and estimated for April 19, 1977, (A) 3.2-km arc, 1300-1900 MST; (B) 48-km arc, 1400-2000 MST; (C) 90-km arc, 1600-2200 MST. Azimuth is defined as viewed from the release position with 0 due North and 90 due East (see Figure 9). Receptor numbers are shown just above each observed concentration value. (D) Time history of observed PDCH and estimated SF_6 concentrations along the 48-km arc for April 19, 1977. Observed PDCH values were multiplied by 3.16 for comparison with estimated SF_6 values (volume of SF_6 divided by volume of PDCH released equals 3.16).

release location. The second moment, σ_y , represents a measure of the puff horizontal dispersion. For these 6-hour periods, the observed lateral dispersion ranged from roughly 22% to 15% of the travel distance downwind. The crosswind integrated concentration (CWIC) value characterizes the amount of pollutant mass seen at the surface. The observed CWIC values at all of the arcs is close to what one would expect if the tracer had become well mixed in the vertical. As shown in Figure 11 (which is typical for all of the simulations), the simulated transport was somewhat south of the observed position along the first two arcs. It is also apparent that the concentrations simulated for the first arc are at least a factor of 5 higher than observed.

Figure 11d provides a comparison of the time history of the puff, as it passed by the 48-km arc. Sampling results are shown for the two-trap sampler which provided 5-minute samples, and a cassette sampler which provided approximately 15-minute samples. These samplers were quite close to the observed position of the 6-hour SF_6. maximum along this arc. The dispersion results are for the simulated position of the maximum, which was somewhat displaced from that observed. The Pasquill dispersion results are in remarkable accord with the tracer results. The similarity results arrive and depart slightly later than observed. The slower transport for the similarity dispersion occurs because the vertical dispersion was less than that simulated by Pasquill dispersion, hence the transport speed was computed over a more shallow layer for the similarity results. These results and those discussed above suggest that the similarity dispersion was underestimating the vertical dispersion for this case.

The primary purpose of this investigation was to assess whether the CALPUFF simulations were in reasonable accord with the observed concentrations. The comparison results presented reveal as yet unexplained differences for the nearest arc, 3.2 km downwind from the release. The simulated pattern of dispersion was displaced as much as 40 degrees from that observed, regardless of how the wind fields were characterized. For all arcs, the lateral dispersion along the sampling arcs was best characterized by both dispersion characterizations when all the surface tower winds were used. Except for the first sampling arc, the simulated maxima along the arcs were typically within a factor of 2 of that observed. The Pasquill simulations were most sensitive to how the wind fields were characterized, showing the most variability between the various wind field results. Having but one puff release limits conclusions to be reached. For this one realization, it would appear that simulations by both dispersion characterizations were in best accord overall with observations when all the low-level winds and upper-air observations were used. And for this case, the similarity dispersion simulations may have underestimated the vertical dispersion.

4.6.3 1980 Great Plains Tracer Study

In this study (U.S. EPA, 1998a), concentration estimates from the CALPUFF dispersion model were compared to observed tracer concentrations from a short-term field experiment (the Great Plains experiment) near Norman, Oklahoma (Ferber et al., 1981) in July 1980. This experiment examined long-range transport of inert tracer

materials to demonstrate the feasibility of using other tracers as alternatives to the more commonly used SF_6. Several tracers were released for a short duration (3-4 hours) and the resulting plume concentrations were recorded at an array of monitors downwind from the source. For the Great Plains experiment, arcs of monitors were located 100 and 600 kilometers from the source.

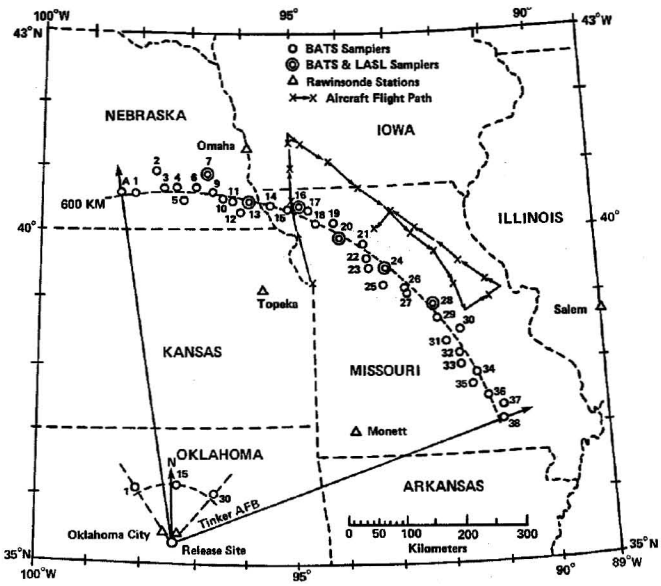

Figure 12. Great Plains field experiment site.

Previous studies have compared the results from the Great Plains experiment to dispersion model results. Carhart et al. (1989) intercompared the results from eight short-term, long-range dispersion models to the Great Plains results and to a longer-term study at the Savannah River Laboratory (not the study discussed in Section 4.6.1). The primary method for evaluating model performance was the use of the American Meteorological Society (AMS) statistical measures (Fox, 1981) and graphical techniques. They concluded that model results compared in space and in time to observations were generally poor and that predictions for a specific location and time for averaging periods less than one day were not reliable. They also noted that unpairing decreases the scatter. They concluded that “model improvement can be made by better representing the wind field. The use of multiple layers seems to improve results substantially.”

The transport and diffusion of a tracer gas was simulated by Moran and Pielke (1995a,b) using the Colorado State University mesoscale atmospheric dispersion modeling (CSU MAD) system, which consists of a prognostic meteorological model coupled to a mesoscale Lagrangian particle dispersion model. Results from several simulations with the model were compared to observations from the Great Plains experiment. Their baseline simulation generally compared favorably to observations for

both arcs although directional errors of up to 20° were apparent. The results also suggest that the nocturnal low-level jet plays an important role in transport and deformation of the tracer plume and that some flow regimes require better temporal resolution of boundary layer winds than is available from the National Weather Service (NWS) twice-daily rawinsondes.

The Great Plains site is shown in Figure 12. Two arcs of monitors were deployed during the field experiment -- 100 and 600 kilometers. For this analysis, two separate grids were defined. For the 100-kilometer arc, a grid extending approximately from 35° N to 36.5°N latitude and from 96° W to 98.5° W longitude was defined. A 42-by-40 horizontal grid with a 10-kilometer resolution was used for this arc. For the 600-kilometer arc, the grid extended from approximately 35° N to 42°N latitude and from 89° W to 100° W longitude. A 44-by-40 horizontal grid with a 20-kilometer resolution was used for this arc.

To adequately characterize the vertical structure of the atmosphere, six layers were defined: surface-20, 20-50, 50-100, 100-500, 500-2000, and 2000-3300 meters. The CALMET preprocessor utilizes NWS meteorological data and on-site data to produce temporally and spatially varying three dimensional wind fields for CALPUFF. Only NWS data were used for this effort and came from two compact disc (CD) data sets (see Appendix C). The first was the *Solar and Meteorological Surface Observation Network* (SAMSON) compact discs, which were used to obtain the hourly surface observations. The following surface stations were used:

Arkansas:	Fort Smith
Iowa:	Des Moines
Illinois:	Springfield
Kansas:	Dodge City, Topeka, Wichita
Missouri:	Columbia, Kansas City, Springfield, St. Louis
Nebraska:	Grand Island, Omaha, North Platte
Oklahoma:	Oklahoma City, Tulsa
Texas:	Amarillo, Dallas-Fort Worth, Lubbock, Wichita Falls

Twice daily soundings came from the second set of compact discs, the *Radiosonde Data for North America*. The following stations were used:

Arkansas:	Little Rock	Nebraska:	North Platte, Omaha
Illinois:	Peoria	Oklahoma:	Oklahoma City
Kansas:	Dodge City, Topeka	Texas:	Amarillo
Missouri:	Monett		

CALMET requires a file of terrain elevations and geophysical parameters in order to prepare the wind fields and other meteorological parameters. The geophysical parameters were derived from geographical information system (GIS) land-use categories. Terrain and land-use data were available on the CALMET, CALPUFF, and

CALPOST Modeling System (version 1.0) CD (see Appendix C). These data are defined with a resolution of 1/6° latitude and 1/4° longitude.

The primary purpose of the Great Plains field study was to demonstrate the efficacy of perfluorocarbons as tracers in atmospheric dispersion field studies. Perfluoromonomethylcyclohexane (PMCH), perfluorodimethylcyclohexane (PDCH), SF_6, and two heavy methanes were released during this experiment. For this analysis, the PDCH emission rates were used since the monitoring data appeared to have a more complete record of PDCH concentrations. The following source parameters were used for this analysis:

Source	Release height (m)	Stack diameter (m)	Exit velocity (m s^{-1})	Exit temp. (K)	Total tracer released (kg)	Length of release (hr)	Emission rate (g s^{-1}) and tracer
Oklahoma (July 8)	10.0	1.0*	0.001	ambient	186	3.0	17.22 PDCH
Oklahoma (July 11)	10.0	1.0*	0.001	ambient	26	3.0	2.41 PDCH

* The stack diameter for each study is the same as was used for the study with the INEL data

For both experiments, the emission rate was assumed to be constant over the entire period of the release, and the release was assumed to be nonbuoyant.

For the July 8 Great Plains experiment, sampling was conducted using two arcs of monitors: 100 kilometers and 600 kilometers as shown in Figure 12. Two separate CALPUFF model runs were made: 1) using Pasquill-Gifford (PG) dispersion parameters, and 2) using dispersion coefficients from internally-calculated σ_v and σ_w from the micrometeorological variables calculated in CALMET (hereafter referred to as similarity dispersion).

Beginning at 1300 LST on July 8, the PDCH and PMCH tracer gases were released at a constant rate for a three-hour period from an open field at the National Severe Storms Laboratory in Norman, Oklahoma. A background concentration for PDCH of 26 ppt (Ferber et al., 1981) was removed from the observed concentrations. The five-hour average modeled and observed concentrations for the 100-kilometer arc on July 8 of the Great Plains field experiment are shown in Figure 13a along with Moran and Pielke's baseline simulation (experiment 4b). Two things are immediately apparent: the monitoring did not capture the entire plume and the observed maximum concentration is very likely less than the simulated maxima. Given the incomplete sampling of the observed plume at 100 kilometers for this release, the statistical measures of the observed plume likely are suspect and are not sufficient to draw conclusions regarding model performance. In comparing the CALPUFF results to Moran and Pielke's simulation, the CSU MAD model placed the maximum about 25°

west of the actual plume. Moran and Pielke's result for the 100 kilometer arc are very similar to the CALPUFF simulations.

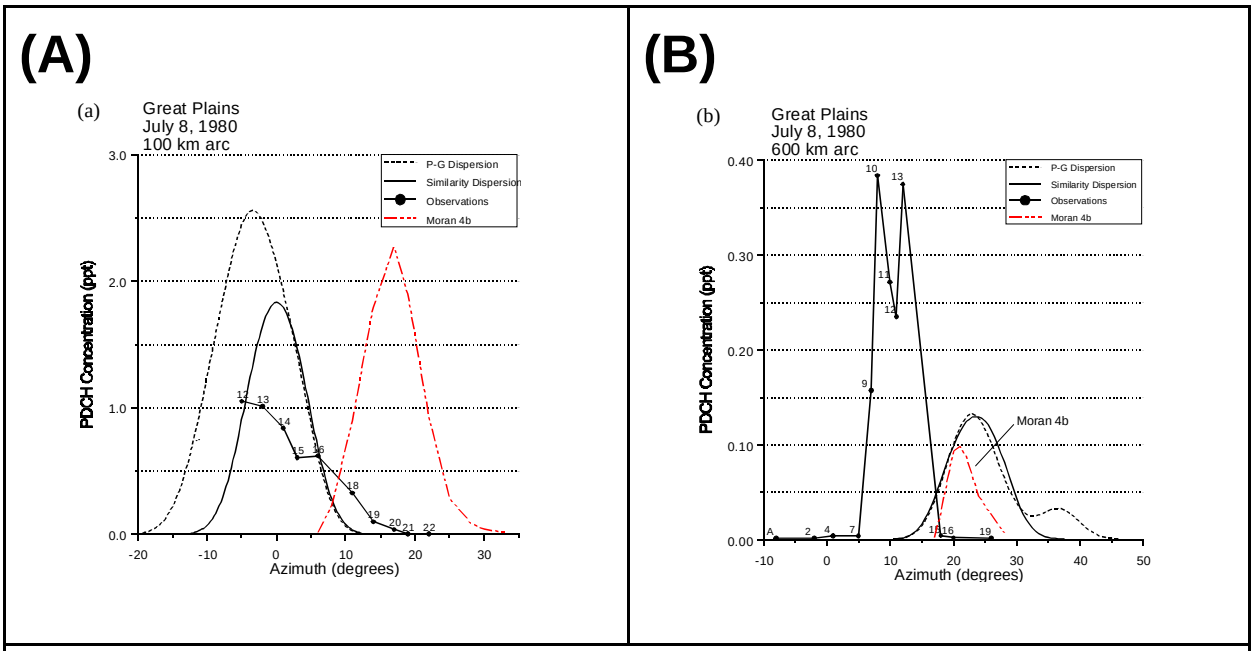

Figure 13. Simulated and observed concentrations for the Great Plains tracer field study for July 8, 1980 for A) 5-hour average concentrations along the 100-km arc, and B) 12-hour average concentrations along the 600-km arc.

The 12-hour average modeled and observed concentrations for the 600-kilometer arc on July 8 are shown in Figure 13b. Two things are apparent: 1) the observed maximum concentration is about three times higher than the simulated concentrations and 2) the maxima of the simulations are in relatively good agreement with each other. As noted above, the tracer arrived at the sampling arc earlier than anticipated and the sampling likely missed some of the tracer material. Ferber et al. (1981) speculate that the plume probably arrived just before the samplers were activated and a small amount of plume material was not collected. As described by Moran and Pielke (1995a), the most likely reason for the earlier-than-expected arrival was the formation of a low-level nocturnal jet. Hoecker (1963), in detailed studies of the low-level jet over the Midwestern plains (from Amarillo, TX to Little Rock, AR) using a series of pibal stations, found that jet speed maxima occur between 300 and 800 meters above local ground. In examining available data for the 1980 Great Plains field experiment, Moran and Pielke (1994) note an approximate doubling of the average nocturnal wind speeds from their daytime values. Examination of the upper air wind profiles for Oklahoma City through the period indicate the presence of a jet between 500 and 1000 meters for the 1200 Greenwich Mean Time (GMT) soundings.

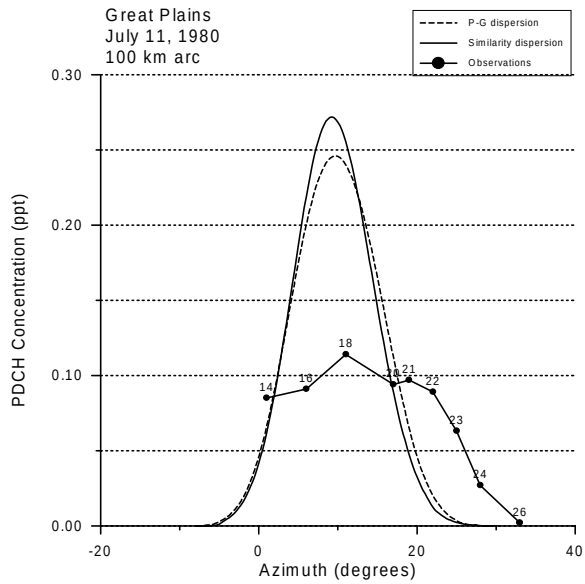

Figure 14. Simulated and observed 6-hour average concentration for the Great Plains tracer field study on July 11, 1980 along the 100-km arc.

Beginning at 1300 LST on July 11, tracer gases were released for a three-hour period using the same system as on July 8. The PDCH was released as an aerosol spray at an average rate of 2.41 g/s, about 1/7 the release rate on July 8. A background concentration for PDCH of 26 ppt was removed from the observed concentrations. The transit time for the observed plume was six hours. The transit time of the simulated plume in CALPUFF using both P-G and similarity dispersion coefficients also was six hours. Therefore, six-hour average concentrations were used in this part of the analysis.

The six-hour average modeled and observed concentrations for the 100-kilometer arc are shown in Figure 14. As with the July 8 study, the monitoring did not capture the entire plume at 100 kilometers, although the peak appears to be a little better defined, with an observed maximum at receptor 18. There were no aircraft flights to assist in determining the western extent of the plume. The simulated plumes using PG and similarity dispersion agree with each other very well, but, as with the July 8 results for the 100-kilometer arc, the peaks are more than twice the magnitude of the observed plume and the simulated lateral dispersion is less than the observed plume. .

As with the 100 kilometer arc for the July 8 study, the question remains - why do the simulated plumes have higher central maxima and narrower dispersion. With a more sophisticated modeling system, Moran and Pielke (1995a,b) encountered similar differences in their examination of the July 8 simulation at 100 kilometers, and they could not explain to their satisfaction why their dispersion model was not able to more closely represent the observed dispersion patterns at the receptor arcs.

4.6.4 1992 Project MOHAVE Tracer Study

In this investigation (Vimont, 1998), the CALMET/CALPUFF modeling system's simulation of tracer gas dispersion was compared with field measurements collected during the 1992 summer intensive monitoring period of Project MOHAVE. The Project MOHAVE tracer monitoring sites used in this analysis were at Dolan Springs (DOSP), Las Vegas Wash (LVWA), Meadview (MEAD), and Overton Beach (OVBE), (Figure 15). The tracer was released from the stack of the Mohave Power Plant (MOPP) in direct proportion to the time-varying sulfur dioxide emissions. The tracer was collected in 24-hour samples starting at 7 AM Mountain Standard Time (MST) at each of the sites, except at MEAD which had two 12-hour samples with start times of 7 AM and 7 PM MST. The monitoring network is not well suited for rigorous model evaluation as it is too sparse. Ideally, a network designed for model evaluation would have arcs of monitors placed at distances of interest (as in the studies mentioned in previous sections of this report). Also, it would be of interest to have sufficiently short sampling intervals so that passage of tracer past and along an arc could be analyzed.

The meteorology is strongly influenced by the east-west river canyon that runs from Las Vegas Wash and past Meadview. The Colorado River sharply turns south at Las Vegas Wash along a north-south transect that connects Las Vegas Wash with the location of the Mohave Power station. Upper air wind measurements were available from three radar profiles located at the Mohave Power Plant (MOPP), Meadview (MEAD), and Truxton (TRUX); RASS temperature profiles were available at MOPP, (Figure 14). Twice-daily balloon soundings (winds and temperature) were available from Dolan Springs (DOSP). Since CALMET requires both winds and temperatures at each upper air station, it was necessary to generate temperature profiles for the radar wind profiles collected at MEAD and TRUX. These were constructed by linear interpolation in time using the temperature profiles at DOSP (DOSP is closer in elevation to MEAD and TRUX, whereas MOPP is 600 to 800 m lower in elevation). The radar winds were reported in both a high resolution mode, and a low resolution mode. The high-resolution data does not extend as high, but provides more details. Thus the high-resolution data were combined with the low resolution data before processing by CALMET.

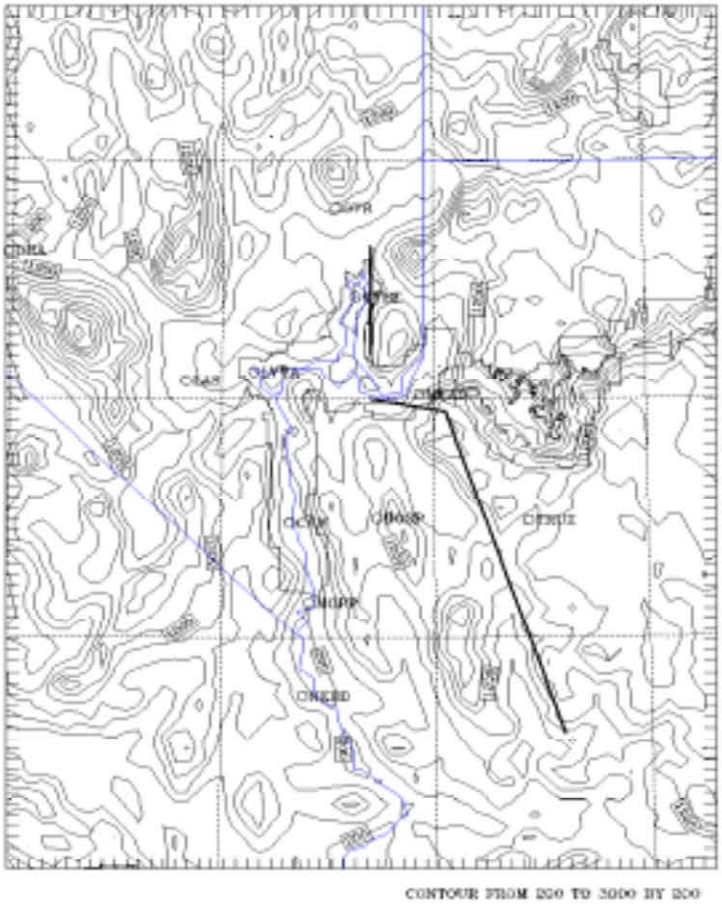

Figure 15. The Project MOHAVE tracer field study collected tracer samples at Dolan Springs (DOSP), Las Vegas Wash (LVWA), Meadview (MEAD), and Overton Beach (OVBE). The tracer was released from the stack of the Mohave Power Plant (MOPP). The bold solid lines are the CALMET “barriers” that were employed in developing the CALMET analyses.

A number of diagnostic model runs were made, and some general conclusions were reached. The initial CALPUFF runs with no complex terrain treatment grossly underestimated concentrations, especially at the nearest monitoring site at DOSP. The inclusion of the partial plume path adjustment terrain treatment option in CALPUFF improved the correspondence of the calculated concentration with the measurements, which is not surprising since several of the monitoring sites are more than 600 m higher than the base of the Mohave Power Plant stack. It was also concluded that the monitoring sites were too sparse to be used in a conventional manner. The narrowness of the dispersing plume meant that even a very small shift of a few kilometers in the plume position would result in major (in some cases orders of

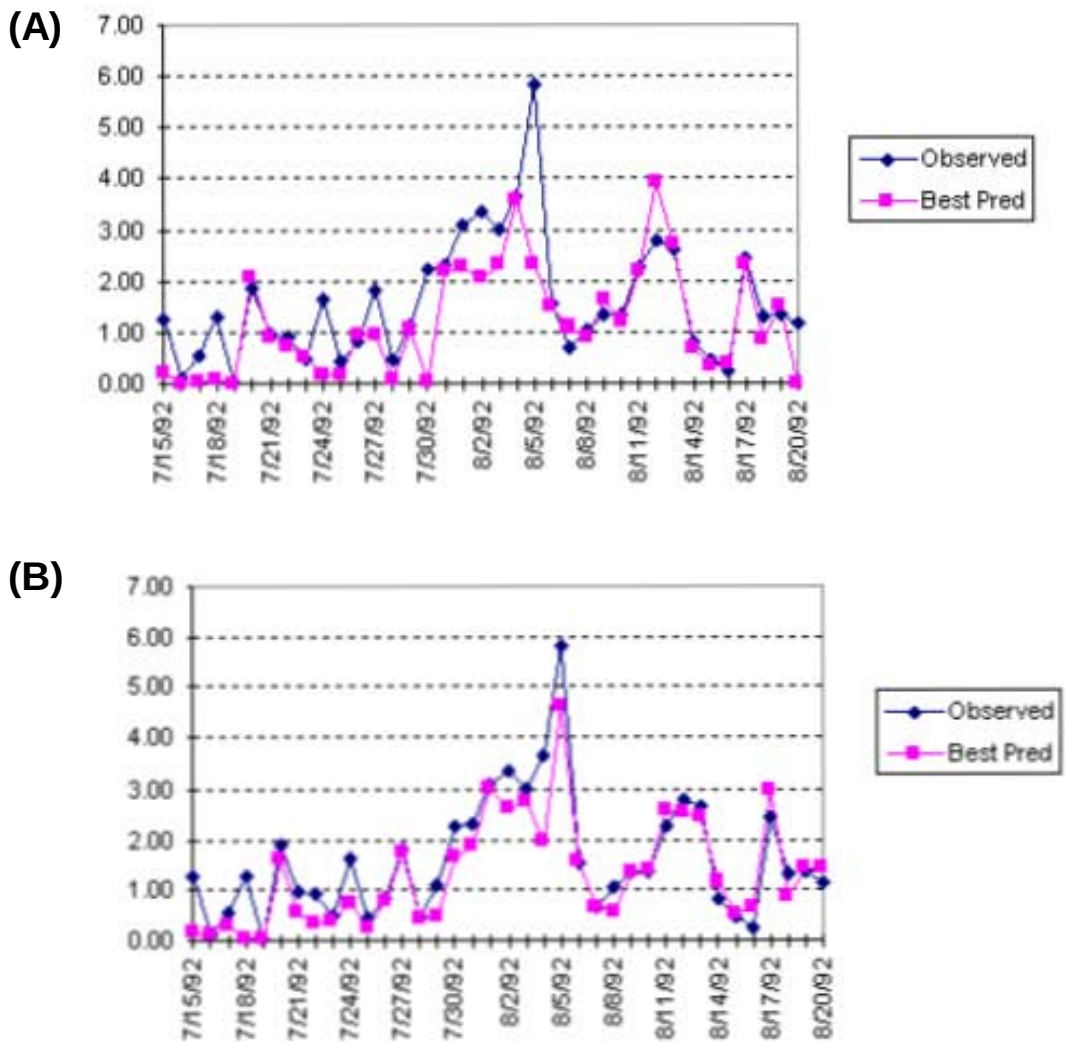

Figure 16 Tracer concentrations (femtoliters/liter) predicted and observed for the Las Vegas Wash (LVW) monitoring site, (A) are results obtained without use of barriers, and (B) are results obtained using barriers in the CALMET processing.

magnitude) changes in the simulated concentration values. To counter this deficiency, eight receptors were placed 15 km around each monitor's location. The estimated concentration in closest correspondence to that measured was selected for use in assessing model performance.

When CALMET was initialized using the wind and temperature profiles from all three sites, the CALPUFF tracer simulation results were in poor agreement with the observations. It was determined that the 1/(distance)^2 initialization used in CALMET was not capturing the fact that each of these sites were located in very unique settings. The TRUX profiler is located at a high elevation in a valley with a southwest to

northeast orientation. The MOPP profiler is located in the Colorado River Valley, which encompasses the DOSP location and continues up to the MEAD monitoring site. The MEAD site is located near the west entrance of the Grand Canyon, which runs east-west. CALMET was modified to allow 'barriers' to be placed in the Step 1 initialization process, so that the influence of observations could be limited to better reflect the unique settings of the profiler locations. The bold solid lines in Figure 15 show the placement of the barriers. Figures 16a and 16b illustrate the differences seen in the simulated concentrations without and with the barriers in the CALMET processing. The correspondence of the simulated tracer concentrations with those monitored seems to have been improved by allowing the barriers to influence the development of the CALMET Step 1 wind fields.

4.7 Comparisons of CALPUFF With ISC3

A sensitivity study comparing the ground level concentration values of CALPUFF (Scire et al, 1995b) with those of the Industrial Source Complex Short Term (ISC3) model (U.S. EPA, 1995c) for steady state and nonsteady state conditions was performed. The study (U.S. EPA, 1998; Eckhoff and Coulter, 1998) was divided into two parts. First, specific CALPUFF model input settings were tested for the best setting for emulating ISC3 under steady-state conditions. In the second part, the same input settings were then used to compare CALPUFF to ISC3 results under nonsteady state conditions.

For the first part of the study, CALPUFF (4.0) was compared with the latest version of ISC3 (Version *96113*). ISC3 was implemented in the 'Regulatory Default' mode and the input file for CALPUFF was configured so as to emulate ISC3 as closely as possible. Point sources were simulated for rural environments free of obstacles and with stack heights of 2 m, 35 m, 100 m and 200 m above ground level. Meteorological data sets were synthesized with fixed meteorological conditions (Pasquill-Gifford stability category, wind speed, and mixing height) and were of duration estimated to be sufficient to advect CALPUFF's puffs to the edge of the domain. A line of 62 receptors out to 100 km was placed along the 360° radial, aligned with the transport wind flow, and spaced at increasing intervals from the source.

For each pair of model runs (CALPUFF and ISC3), a residual concentration was computed at each of the 62 receptors. From the 62 residuals (one for each receptor), a mean, standard deviation (σ_R), and sum of residuals squared were computed. The mean provides an indication (sign) of bias along the receptor radial. The variance of the residuals provides general indication of the variance along the receptor radial. Because many of the absolute residuals were quite small, the sum of the residuals squared was also computed to provide a relatively robust indicator of accord along the receptor radial. A Fractional Bias equation, FB = 2*(CALPUFF-ISC)/(CALPUFF+ISC) was also computed. The steady state agreement between CALPUFF and ISC3 was very good. Minimum and maximum fractional bias values of -0.18 and 0.06 are an

indication of how well CALPUFF, with the slug model invoked, can emulate ISC3 in a steady-state environment using point source input data.

Having confirmed that the dispersion algorithms within CALPUFF do emulate quite well those within ISC3, the second part of the study was to compare modeling results when the meteorological conditions were allowed to varying each hour. Hourly meteorological data processed for input into ISC3 were selected from three stations to simulate three climatically different regions of the United States: 1991 Boise, Idaho; 1990 Medford, Oregon; and 1964 Pittsburgh, Pennsylvania. Each set contains a year of hourly averaged values of wind speed, wind direction, ambient temperature, stability class, and mixing heights. In these simulations, wind fields were not generated for the CALPUFF simulations. Instead, the ISC option was used, which allows CALPUFF to operate using meteorological data processed for input to ISC3. This means that the meteorology for these simulations is assumed to be everywhere the same, over the entire CALPUFF computational domain. This admittedly artificial assumption for the CALPUFF meteorology at least insured that the only reason for differences in the modeling results, resulted from the fundamental differences in the treatment of transport between a plume and a puff model.

The Boise data were selected because they were obtained in a river valley which has highly directional wind flows. More than 33% of the recorded winds have a northwesterly component and more than 33% of the winds have a southeasterly component with the majority of those winds having speeds greater than two m/s. Some of the modeled puffs were expected to be transported directly to the most distant receptors. The Medford data were selected because they were obtained in an area surrounded by mountains with a high number of calm wind hours. In 1990, 22% of the Medford Oregon winds were calm winds (<1 m/s). This compares to the average of 6.5% occurrence of calm winds for the other two sites. During calm wind events, CALPUFF calculates concentrations while ISC3 does not calculate concentrations. ISC3 treats the hour as missing when determining concentration averages. There was an expectation that there would be large differences in concentration averages because of the high number of calm winds. The Pittsburgh data were selected because the recording site is located on an open plain above a river valley and that the data have been used as a standard test set for a number of years. The wind directions and wind speeds are fairly well distributed, although there is a tendency for southwesterly winds.

The main receptor placement consisted of 15 rings of 36 receptors each, with receptors spaced every 10 degrees starting at 360 degrees. The rings were spaced at distances of 0.5, 1, 2, 3, 5, 10, 15, 20, 30, 50, 100, 150, 200, 250, and 300 km from the

Table 8. Characteristics for point sources used in the CALPUFF/ISC3 comparisons.				
Stack Height (m)	Emission Rate (g/s)	Exit Velocity (m/s)	Stack Diameter (m)	Exit Temperature (K)
2	100	10.0	0.5	300
35	100	11.7	2.4	432
100	100	18.8	4.6	416
200	100	26.5	5.6	425

source. Four point sources (Table 8) were used in these ISC3/CALPUFF comparisons with hourly varying meteorology. For each year of hourly meteorology, and for each of the 15 rings of receptors, the highest and second-highest concentration was determined for four averaging times (1-hour, 3-hour, 24-hour, and annual) for each model. It was anticipated that some differences would be seen in the simulated maxima, since ISC3 ignores hours with wind speed less than or equal to 1 m/s (calms), for which CALPUFF continues to process, and because ISC3 can not treat the consequences of a flow reversal between hours, a situation easily interpreted by a puff model. Even though such differences were anticipated, the magnitude of these differences, and sensitivity to release height was not known.

As a case study, a ten-hour period was examined to determine the cause of large differences detected in the concentrations simulated by the two models using the Boise meteorological data. The large differences were detected 5 to 15 km downwind from the 2 -m point source for Hour 62 of the simulation, following a 4 hour period of calm winds and then a wind reversal. Figure 17a illustrates the distribution of the pollutant mass, in which emissions from particular hours, preceding Hour 62 have been depicted so that it is possible to see how the sequence of events preceding Hour 62 has affected the results seen. Starting with Hour 52 there was a 5-hour period for which the winds were from the east-southeast. Then there was a period of 4 hours of calm winds, which was followed by a 180-degree wind shift for 2 hours. Thus the pollutant mass which had started out moving towards the west-northwest, for the last two hours is seen moving back towards the southwest. As illustrated in the figure, the result is that a broad area upwind (in terms of Hour 62) is being affected by emissions that were released during Hours 52-60. The subsequent superposition of all of the puffs is shown in Figure 17b. For receptors 5 to 12 km southwest of the stack, the superposition of all the puffs results in concentration values that are more than a factor of two greater than that simulated by ISC3 for Hour 62. During one of the calm hours, Hour 57, the emissions were simulated to penetrate a low-level inversion. CALPUFF

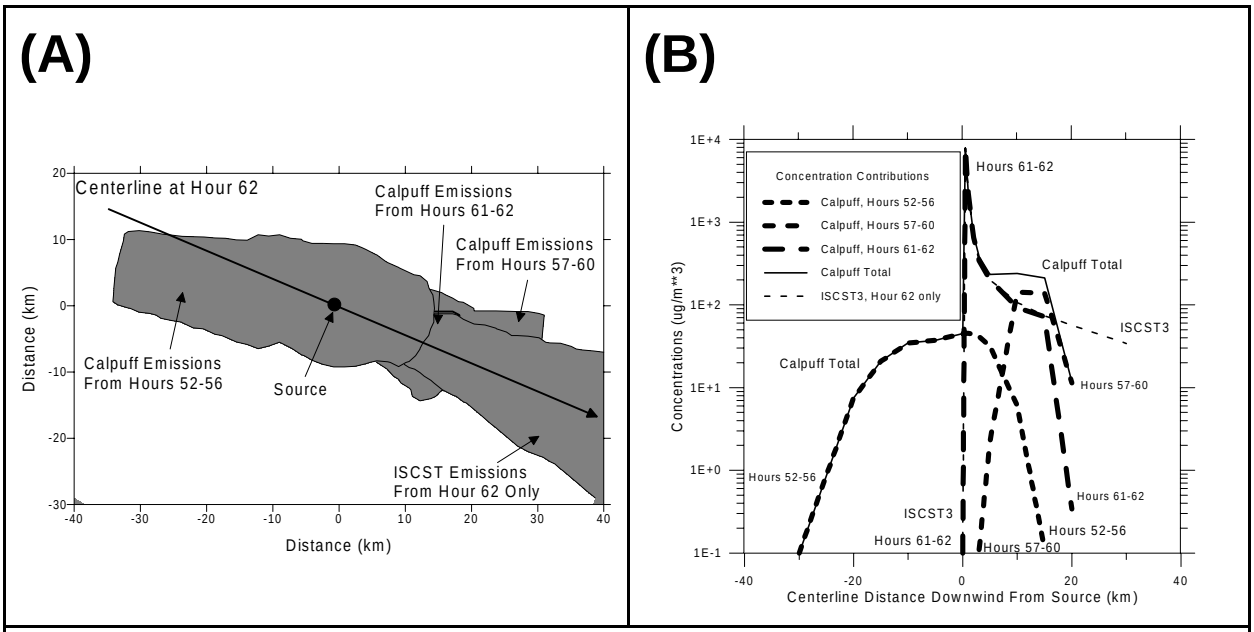

Figure 17. Case study of a ten-hour period of simulated dispersion by CALPUFF. (A) depicts impacts for Hour 62, showing contributions from emissions released prior to Hour 62, (B) depicts centerline concentrations from CALPUFF and ISC.

tracked the puffs and the subsequent fumigation to the ground once the inversion grew to encompass the puffs which were aloft.

The ten-hour example just described is illustrative of how differences can arise. It also serves notice that large differences can arise, and that these differences may arise from a rather complicated history of events. Both the sequence of events, as well as the dispersiveness of the atmosphere are important in understanding the puff simulation results. Unlike in plume simulations, the concentration results obtained for a given hour are unlikely to be understood simply by knowing the meteorology for the given hour. The sequence of the meteorological conditions leading up to the hour in question may be all important.

For each of the three sites, the results for each averaging time were summarized by plotting on a common graph the percent difference, PD = 100(C-I)/I, where C equals the highest (or second-highest) CALPUFF concentration along a receptor ring, and I equals the highest (or second-highest) ISC3 concentration along the same receptor ring for the given averaging time. Figure 18 is an example of some of the CALPUFF/ISC3 comparison results obtained by this sensitivity study. Illustrated in the figure are results for the Medford meteorology, and the results shown are for the 1-, 3-, 24-hour and annual average comparisons of the second-highest concentration values for each of the 15 receptor rings. As each receptor ring is at a prescribed distance, the results illustrate as a function of downwind distance and source-type whether CALPUFF is providing higher (PD>0) or lower (PD<0) concentrations than ISC3. The Medford

meteorological data had the highest occurrence of calm wind conditions, and some of the largest differences. CALPUFF was seen to provide concentration values greater than ISC3, for this site for all averaging times. It is instructive to note that CALPUFF can produce nonzero concentration values at the base of an elevated point source release (when flow reverses and pollutants previously released are transported back towards the source). ISC3 can never produce such an effect. It is also instructive to note that CALPUFF can yield much greater concentrations than ISC3 at most any distance downwind and for most any averaging time. The exact timing and distance downwind of such occurrences is dependent on the sequence of meteorological events, but typically can occur whenever there is a period of calm winds of extended length (say more than three hours in duration).

Figure 19 provides a sense of the differences to be seen between sites. Here annual averages are compared for each site. Typically, the greatest differences seen between the two models are seen in the shorter averaging times. The comparisons of the annual averages most clearly illustrate that as release height increases, CALPUFF tends to increasingly provided higher concentration impacts in comparison to ISC3. Also the comparisons of the annual averages best illustrate the occurrences of nonzero concentration values being simulated by CALPUFF and the lack thereof by ISC3. The effect on the model simulations and resulting comparison of concentration values of the high incidence of calm wind conditions (~23%) at Medford is apparent. The Pittsburgh and Boise meteorological data had similar incidences of calm wind conditions (7% and 6% respectively), but the Boise data was highly directional, with 33% of the wind towards the southeast and 33% of the winds towards the northwest (suggestive of high incidences of flow reversals). Thus it is that the Boise comparisons show CALPUFF yielding higher percentage difference in the annual averages than those seen using the Pittsburgh meteorological data.

In the above comparisons discussed, it is important to remember that no terrain effects on the meteorology were modeled (other than that which is inherent in the climatology of the surface weather observations). Hence, the percentage differences seen could have occurred at any of the sites, given the correct sequence of meteorological events. In this sensitivity analysis, one year of data was used from each site. The site-to-site differences is seen to be large. In the comparisons to be discussed in the next section, several years of data are used from one site.

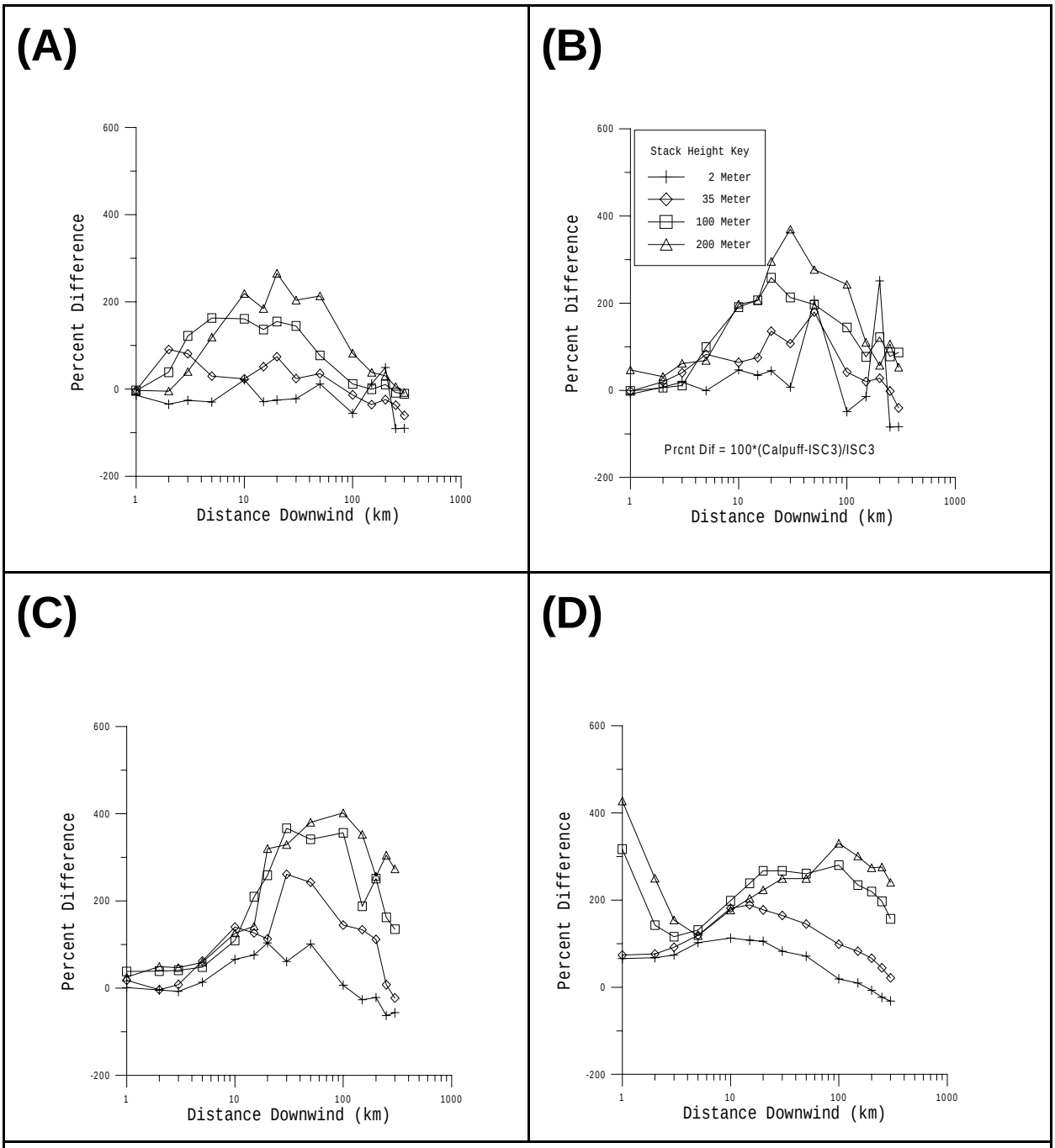

Figure 18. Percent differences (CALPUFF versus ISC3) as a function of downwind distance for the second-highest concentrations; (A) 1-hr, (B) 3-hr, (C) 24-hr, and (D) annual averages. Data are for Medford, Oregon.

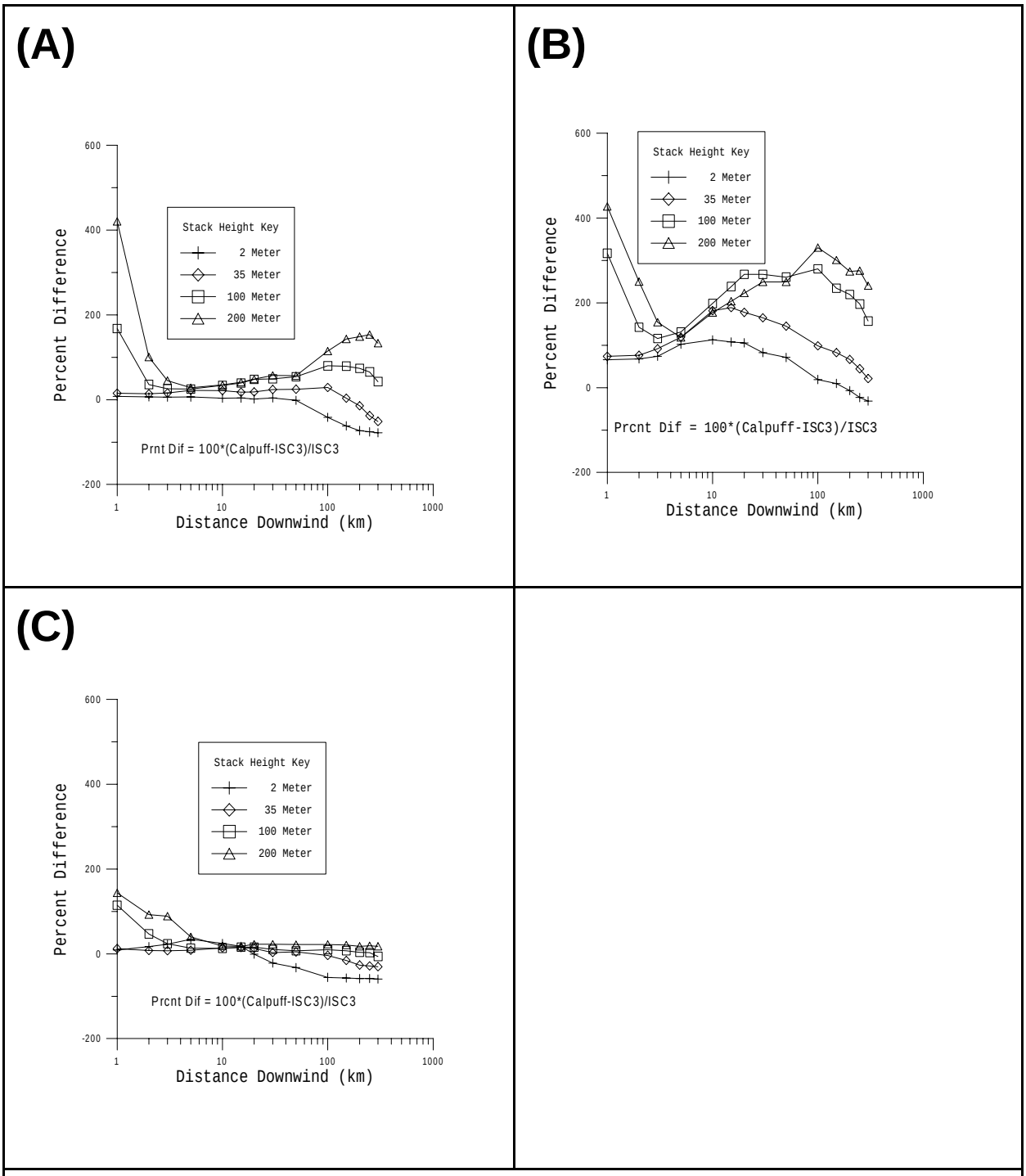

Figure 19. Percent differences (CALPUFF versus ISC3) as a function of downwind distance for the annual average: (A) Boise, (B) Medford, and (C) Pittsburgh.

4.8 CALPUFF SCREEN

By far, one of the most demanding tasks in performing refined puff model simulations is to successfully develop a valid time and space varying characterization of the meteorological conditions for use by the CALPUFF puff dispersion model. The processors that format and organize the input data to CALMET are not presently user-friendly and demand strong computer skills. Often special custom routines are needed to format available data into the acceptable formats for use by CALMET. Even if the logistics of manipulating the data were simplified, developing realistic characterizations of the time-varying three-dimensional wind fields will always require specialized skills. Developing mesoscale and microscale meteorological characterizations requires having not only the specialized understanding of micrometeorological wind effects, but also the experience and expert judgement to know when a characterization developed by the meteorological processor is unreasonable. Furthermore, to review and critique the CALMET results requires strong computer skills for visualization of the CALMET results, or for listing out for special inspection portions of the CALMET results.

In this section, we summarize the results from a study in which a methodology was tested whereby CALPUFF could be used with a simplified set of meteorological data, for the purpose of providing screening estimates of concentration and deposition impacts (U.S. EPA, 1998b). The methodology was tested in two ways: 1) five years of hourly meteorology were used to develop data for assessing the year-to-year variability, and 2) one year of hourly meteorology was fully processed through CALMET to assess whether the screening methodology devised did indeed provide concentration impacts greater than would be developed using a fully developed set of meteorology.

4.8.1 Screening methodology

As a design goal, it was our intention to minimize the effort needed to create the meteorological input for use by CALPUFF. CALPUFF has a built-in mode whereby it can use the meteorological data file generated by PCRAMMET for the Industrial Source Complex Short Term (ISCST3) model, thus bypassing the need to run CALMET.

The following approach was devised for running CALPUFF in a screening mode to estimate ground-level concentrations over a large area:

1) generate five years of ISCST3 input meteorology using PCRAMMET,

2) generate an ISCST3 control file and use the ISC2PUF conversion program to create the CALPUFF control file,

3) use the CALPUFF Graphical User Interface (GUI) to finalize the CALPUFF control file before running the CALPUFF model,

4) run CALPUFF with the ISCMET.DAT data option, and

5) pick the maximum concentration for each pollutant, for each distance and averaging time modeled (see discussion below on receptor placement).

Generating ISC3 input meteorology

PCRAMMET can be used to generate the meteorological data files for CALPUFF. Using hourly surface observations and twice-daily mixing heights, PCRAMMET computes atmospheric stability in the form of Pasquill-Gifford (PG) categories and rural and urban mixing heights. These data, along with the wind direction, wind speed, and temperature, are read directly by CALPUFF without any modification to the data file. It is recognized that this characterization of the meteorology will not vary spatially as in a refined modeling effort, and the consequent differences will be significant as the terrain becomes more rugged and complicated. As is known by those experienced in puff dispersion modeling, one can make conservative choices and assumptions, but it is difficult to guarantee that the results obtained will always be more conservative (but not onerously so) than that derived using fully developed time and space varying meteorological input data. In order to encourage the resulting concentration estimates to be higher than would be obtained using a refined set of meteorology, we have made conservative assumptions as to how the receptors will be placed, and which concentration values will be selected for use.

To perform dry deposition calculations, the surface roughness, friction velocity, and Monin-Obukhov length are required. These parameters can be computed by PCRAMMET and written to an output file for use. In order to estimate these additional parameters, several additional input values are required by PCRAMMET, including: surface roughness at the site where the wind measurements are taken (usually an airport), surface roughness at the site where the model is to be applied, noon-time albedo, Bowen ratio, and fraction of the net radiation absorbed by the ground.

For the test results to be discussed, we applied the screening methodology to the region about Oklahoma City depicted in Figure 12. We had previously developed the CALMET terrain and land-use files as discussed in Section 4.6.3. A surface roughness length at the measurement site (Oklahoma City airport) of 0.10 meters was assumed. An average roughness length of 0.34 meters was computed from the GEO.DAT file created for the entire modeling domain, as well as, an average noon-time albedo of 0.15 and Bowen ratio of 1.00. A value of 0.15 was assumed for the fraction of net radiation absorbed by the ground.

ISC3 control file settings

Using this proposed methodology, the control file and meteorology input can be created as if preparing for an application of the ISCST3 dispersion model. This approach has the advantage that many dispersion modelers are familiar with both the meteorological data and control file structures. The rural dispersion coefficients with the regulatory default settings were selected, which include use of stack-tip downwash, buoyancy induced dispersion, final plume rise, default wind speed profile exponents, and default vertical potential temperature gradient. Averaging times for the model runs were 1-hr, 3-hr, 24-hr, and annual averages.

A polar grid was used to define the receptor locations. CALPUFF does not accept a polar grid directly. Receptors must be a subset of the CALPUFF computational domain (which is a subset of the meteorological domain), i.e., a Cartesian grid, or they must be discrete receptors. The ISC2PUF program can convert a polar grid and associated terrain to discrete receptors with terrain. The ISC2PUF limits the number of receptors that can be processed to 1200. Hence very large applications, may require two or more runs of this program followed by merging the results into a single CALPUFF control file.

For the test results to be discussed, the following polar receptor networks were used:

Distance (km)	Receptor Spacing Along Each Ring	Number of Receptors	Distance Along Ring Between Receptors
1, 2, 3, 5, 10, 15, 20, 30, 50	every 10°	324	0.2 - 8.7 km
75, 100, 150, 200, 250, 300	every 5°	432	6.5 - 26.2 km

These two polar networks result in 756 receptors, well below the limit of about 1200.

CALPUFF control file settings

The CALPUFF system includes a program (ISC2PUF) that translates an ISCST3 control file to a CALPUFF control file. The converted control file must be edited prior to running CALPUFF. This can be accomplished in one of two ways: using a text editor to modify the control file directly, or using the CALPUFF graphical user interface (GUI) to guide the user through the options.

The CALPUFF control parameters that must be set by editing the ISC2PUF generated CALPUFF control file include: the use of puffs or slugs, and the type of dispersion - Pasquill-Gifford or internally-computed σ's. Also to be considered are the pollutants of interest, modeling of chemical transformations, and modeling dry deposition processes.

Pollutants: The transformation pathways for five active pollutants are treated by the MESOPUFF II scheme in CALPUFF: SO_2, $SO_4^=$, NO_x, HNO_3, and NO_3^-. Since haze and visibility are of concern in areas such as national parks, CALPUFF is most likely to be applied to model sulfates and nitrates. For the testing results to be presented, the focus was on SO_2 and $SO_4^=$.

Slug model versus puff model: The slug model was used, with the set of default options for slugs.

Dispersion coefficients: Pasquill-Gifford dispersion coefficients for both the screening and refined CALPUFF modeling were used.

Concentration estimates: CALPUFF was run initially for both the refined (one year) and screening modes (five years) without any chemistry or deposition. This provided 'baseline' concentration estimates without the effects of chemistry and deposition. CALPUFF was then run for one year with chemistry and deposition activated.

Chemical transformations: There are two transformation options in CALPUFF: 1) MESOPUFF II mechanisms and 2) a file with a diurnal cycle of transformation rates. The MESOPUFF II option requires relative humidity as one of the input variables for chemical transformations. However, this variable was not present in the current ISCST3 meteorological data file. The second mode requires a file of diurnal transformation rates specified by the user. In this mode, transformation rates are spatially uniform but provides for some temporal variability. The second method, with the file of transformation rates, was used in this modeling effort.

For the test results to be discussed, we used a 3.0 %/hr transformation rate for daylight hours and 0.2 %/hr at night for the SO_2 to $SO_4^=$ transformation. These rates were used for both CALPUFF refined and screening modes. The daytime period was defined as 0700 to 2000 LST, which biases the daylight period towards a summer day and should result in production of more sulfates.

Dry deposition: In CALPUFF, deposition can be modeled as either particle or gas, depending on the pollutant. To estimate deposition, the surface roughness length, surface friction velocity, and Monin-Obukhov length are estimated by CALMET and vary temporally and spatially when CALPUFF is run in a refined mode. In the screening mode, though, these variables are specified for each hour on the 'extended' data record in the meteorological file. PCRAMMET was run to generate these extended data records for the CALPUFF screening mode.

To compute dry deposition of particles or gases, CALPUFF requires one of the following: 1) a file of the diurnal variation of deposition velocities for each pollutant modeled, or 2) specification of the mass mean diameter, geometric standard deviation,

and number of particle size intervals to evaluate the effective particle deposition velocity. For the latter option, CALPUFF has default parameters for several pollutants, including SO_2 and $SO_4^=$. For this modeling effort, we used the second option with the gaseous SO_2 default parameters and the particulate $SO_4^=$ default parameters.

4.8.2 Year to year variability

Five years of meteorological data were processed through PCRAMMET to create the necessary input meteorology for the CALPUFF screening model runs. Oklahoma City was used for the hourly surface observations and Oklahoma City/Norman for the upper air data. Data from the Solar and Meteorological Surface Observation Network (SAMSON) compact disc (see Appendix C) were used to obtain the hourly surface data. The twice-daily mixing heights were retrieved from EPA's Support Center for Regulatory Air Models (SCRAM) system. The mixing height data on SCRAM restricted the period of choice from 1984 through 1991. Oklahoma City for 1985-1988 were used for this modeling effort. There were no mixing height data for 1989 on SCRAM. The upper air station changed from Oklahoma City to Norman in 1989. Since Norman is only 25-30 kilometers from Oklahoma City, data from Norman for 1990-1991 was used. There were no periods of missing data for Oklahoma City that required filling. There were five 2-hour periods of unfilled mixing heights for the two years of data at Norman. Following EPA guidance, the mixing heights were filled by linearly interpolating between the hours before and after the missing periods to fill in the mixing heights.

The 2-m, 35-m and 200-m point sources listed in Table 8 were used in this assessment. The rings of receptors (as listed earlier) were placed around each source, and the five years of ISC-type meteorology were processed by CALPUFF. For this assessment of year to year variations, inspection was made of the variations seen in the highest 1-hr, 3-hr, 24-hr and annual simulated SO_2 concentration, along each receptor ring. Table 9 summarizes the maximum and minimum value seen for C/Cavg, where C is the maximum concentration seen in any one year along a receptor ring for a particular source and averaging time, and Cavg is the average of the five values seen for this source along this ring for the five years simulated. Rather than list the results separately for each of the 15 receptor rings, we have compiled the results for three groups, with group 1 having four receptor rings at distances 1-, 2-, 3-, and 5-km; group 2 having five receptor rings at distances 10-, 15-, 20-, 30-, and 50-km; and group 3 having six receptor rings at distances 75-, 100-, 150-, 200-, 250-, and 300-km. These three groups subjectively relate to near-field impacts (group 1), mesoscale impacts (group 2), and longer-range impacts (group 3).

Table 9. Summary for three hypothetical sources and for four averaging times in the variation seen in the ratio C/Cavg, where Cavg is the average of the 5 maximum SO_2 concentrations for a receptor ring and averaging time, and C is the maximum SO_2 concentration simulate during one of the five years. The variations listed in C/Cavg reflect both variations seen with the distance range and variations over the five year period of the analysis.

		2-m Source		35-m Source		200-m Source	
1-Hour	Range	Min	Max	Min	Max	Min	Max
	1-5 km	0.79	1.52	0.89	1.14	0.68	2.05
	10-50 km	0.65	1.86	0.76	1.47	0.47	2.32
	75-300 km	0.56	1.66	0.72	1.23	0.44	1.74
3-Hour	1-5 km	0.83	1.26	0.89	1.21	0.80	1.49
	10-50 km	0.58	1.43	0.80	1.48	0.58	2.19
	75-300 km	0.59	1.87	0.60	1.52	0.71	1.51
24-Hour	1-5 km	0.85	1.16	0.80	1.26	0.75	1.29
	10-50 km	0.64	1.55	0.79	1.45	0.77	1.60
	75-300 km	0.61	2.13	0.59	1.52	0.68	1.41
Annual	1-5 km	0.90	1.11	0.88	1.13	0.83	1.26
	10-50 km	0.88	1.13	0.90	1.12	0.88	1.17
	75-300 km	0.81	1.29	0.89	1.25	0.86	1.17

As averaging time increased, there was less variation between years. For instance, for the 75 to 300 km receptor rings, the ratio of the one-hour maxima to the five-year average one-hour maxima varied from 0.45 to 2.30. Whereas the ratios for the annual-averages ranged from 0.80 to 1.30. For these results it is concluded that we might expect variation in the maximum concentrations of at least 20 to 30 percent.

4.8.3 SO_2 concentrations

One of the comments received at the Sixth Modeling Conference was the perception that the Phase 1 (Level I) screening procedure (U.S. EPA, 1993) was too conservative to be of practical use. Thus a second part of developing a new screening methodology was to test the results obtained with the new methodology with those that would be obtained in a refined modeling analysis. Table 10 summarizes the maximum

Table 10. Summary for three hypothetical sources and for four averaging times in the variation seen in the ratio Cs/Cr, where Cs is the SO_2 maximum concentration for a receptor ring and averaging time using CALPUFF with ISC meteorology, and Cr is the second highest SO_2 concentration simulated for the same ring using CALPUFF with CALMET meteorology. Results were generated for only 1990, so the minimum and maximum values for Cs/Cr, reflect variations seen over the receptor rings included in the range.

		2-m Source		35-m Source		200-m Source	
1-Hour	Range	Min	Max	Min	Max	Min	Max
	1-5 km	0.59	1.31	1.03	1.51	0.86	3.07
	10-50 km	0.74	1.30	0.87	1.86	1.27	3.29
	75-300 km	0.99	3.20	1.55	2.09	0.68	1.09
3-Hour	1-5 km	0.82	1.42	1.02	1.08	0.77	1.56
	10-50 km	0.88	1.43	0.80	1.53	0.72	2.71
	75-300 km	0.96	3.89	1.17	3.35	0.73	1.04
24-Hour	1-5 km	0.95	1.00	0.86	0.98	0.73	0.99
	10-50 km	0.88	1.21	0.86	1.28	0.92	1.54
	75-300 km	1.57	4.48	1.11	2.55	0.96	1.50
Annual	1-5 km	1.28	1.37	1.41	1.47	0.58	1.13
	10-50 km	1.49	2.28	1.59	2.29	1.16	1.30
	75-300 km	1.82	3.47	1.85	2.89	1.07	1.27

and minimum value seen for Cs/Cr, where Cs is the maximum SO_2 concentration seen for 1990 along a receptor ring for a particular source and averaging time using the CALPUFF with ISC meteorology (a screening estimate), and Cr is the second-highest SO_2 concentration seen along the same receptor ring resulting from using the CALPUFF with fully developed CALMET meteorology (a refined estimate). Comparing the CALPUFF screening estimate of the maximum concentration along a ring versus the second-highest concentration from a refined model run, provides an assessment of whether the new screening methodology is a conservative screening estimate.

In each of the three ranges, instances can be found where the maximum SO_2 concentration obtained using ISC meteorology as input to CALPUFF (screening estimate), Cs, was not as high as the second-highest concentration obtained from using CALMET meteorology as input to CALPUFF (refined analysis), Cr. It is important to

remember that these comparisons are between the maximum screening estimate found anywhere along the receptor ring and the refined modeling results for the maximum of the second-highest concentrations found anywhere along the ring. If an actual source were being modeled for a particular Class I area, we would anticipate that it is quite likely that the refined model's estimate of the highest of the second-high concentrations for the segment of a receptor ring passing through the Class I area would be lower than what would be found anywhere around the receptor ring.

For the receptor rings at 75-km to 300-km, the Cs/Cr ratios for the 1-hour comparisons range from 1.00 to 3.0 for the 2-m source, and from 0.70 to 1.10 for the 200-m source. As averaging time increases, the screening estimate of the maximum concentration tends to be greater than the second-highest concentration obtained in the refined analysis. The IWAQM concludes the new screening method (ISC meteorology as input to the CALPUFF model) provided conservative estimates of maximum SO_2 concentration values, that were not overly conservative for practical use. Although there is a finite possibility for the refined analyses to develop higher concentration impacts, the likelihood of this result is low for specific source-receptor pairings.

4.8.4 $SO_4^=$ concentrations

Table 11 summarizes the maximum and minimum value seen for Cs/Cr, where Cs is the maximum sulfate concentration seen for 1990 along a receptor ring for a particular source and averaging time using the CALPUFF with ISC meteorology, and Cr is the maximum sulfate concentration seen along the same receptor ring resulting from using the CALPUFF with fully developed CALMET meteorology. In each of the three ranges in Table 11, instances can be found where the screening estimate for sulfate concentration, Cs, is not as high as that obtained from the refined analysis, Cr. The 24-hour ambient sulfate concentrations are typically used in long-range haze impact assessments. For the 24-hour averaging time, the 2-m source maximum sulfate concentrations obtained with CALPUFF using ISC meteorology are typically greater than were obtained for this site in 1990 using CALPUFF with CALMET meteorological data. For the 200-m release, the CALPUFF screening estimates are less than that obtained using CALPUFF with CALMET meteorology.

Table 11. Summary for three hypothetical sources and for four averaging times in the variation seen in the ratio Cs/Cr, where Cs is the maximum sulfate concentration for a receptor ring and averaging time using CALPUFF with ISC meteorology, and Cr is the maximum sulfate concentration simulated for the same ring using CALPUFF with CALMET meteorology. Results were generated for only 1990, so the minimum and maximum values for Cs/Cr, reflect variations seen over the receptor rings included in the range.

		2-m Source		35-m Source		200-m Source	
1-Hour	Range	Min	Max	Min	Max	Min	Max
	1-5 km	0.52	0.89	0.80	2.12	0.56	1.72
	10-50 km	0.44	0.73	0.65	1.74	0.72	1.16
	75-300 km	0.76	2.57	0.58	2.11	0.33	0.51
3-Hour	1-5 km	0.42	0.76	0.91	1.02	0.42	1.27
	10-50 km	0.50	0.72	0.38	1.15	0.65	1.55
	75-300 km	0.56	3.25	0.54	2.16	0.25	0.50
24-Hour	1-5 km	0.62	1.04	0.55	0.83	0.30	0.70
	10-50 km	0.61	0.91	0.36	0.50	0.32	1.39
	75-300 km	0.58	3.07	0.38	1.51	0.16	0.33
Annual	1-5 km	1.10	1.17	1.23	1.43	0.47	0.89
	10-50 km	1.20	2.02	1.16	1.52	0.82	0.93
	75-300 km	2.00	3.20	1.50	1.88	0.68	0.80

4.8.5 SO_2 deposition

Table 12 summarizes the maximum and minimum value seen for Cs/Cr, where Cs is the maximum SO_2 deposition seen for 1990 along a receptor ring for a particular source and averaging time using the CALPUFF with ISC meteorology, and Cr is the maximum SO_2 deposition seen along the same arc resulting from using the CALPUFF

Table 12. Summary for three hypothetical sources and for four averaging times in the variation seen in the ratio Cs/Cr, where Cs is the maximum SO_2 deposition for a receptor ring and averaging time using CALPUFF with ISC meteorology, and Cr is the maximum SO_2 deposition simulated for the same ring using CALPUFF with CALMET meteorology. Results were generated for only 1990, so the minimum and maximum values for Cs/Cr, reflect variations seen over the receptor rings included in the range.

		2-m Source		35-m Source		200-m Source	
1-Hour	Range	Min	Max	Min	Max	Min	Max
	1-5 km	0.95	1.29	0.81	0.96	0.33	0.99
	10-50 km	0.69	1.47	0.48	1.16	0.28	1.03
	75-300 km	0.70	1.18	0.85	1.27	0.23	0.62
3-Hour	1-5 km	0.73	0.81	0.73	0.78	0.26	0.60
	10-50 km	0.52	1.06	0.59	0.91	0.27	0.87
	75-300 km	0.70	1.05	0.71	1.47	0.27	0.47
24-Hour	1-5 km	0.65	0.70	0.50	0.55	0.16	0.55
	10-50 km	0.80	1.14	0.55	0.63	0.44	0.62
	75-300 km	1.04	1.25	0.58	1.11	0.41	0.77
Annual	1-5 km	1.16	1.00	0.90	0.99	0.30	0.64
	10-50 km	1.32	1.76	1.14	1.71	0.70	0.91
	75-300 km	1.50	2.54	1.48	2.13	0.89	1.02

with fully developed CALMET meteorology. In each of the three ranges in Table 12, instances can be found where the screening estimate of SO_2 deposition, Cs, is not as high as that obtained from the refined analysis, Cr. For SO_2 deposition, the annual or seasonal average deposition is of most interest. For the lower release heights of 2-m and 35-m, the maximum annual SO_2 deposition obtained with CALPUFF using ISC meteorology are consistently greater than were obtained for this site in 1990 using CALPUFF with CALMET meteorological data. For the 200-m release, the CALPUFF screening estimates of SO_2 deposition are similar to those obtained using CALPUFF with CALMET meteorology.

Table 13. Summary for three hypothetical sources and for four averaging times in the variation seen in the ratio Cs/Cr, where Cs is the maximum sulfate deposition for a receptor ring and averaging time using CALPUFF with ISC meteorology, and Cr is the maximum sulfate deposition simulated for the same ring using CALPUFF with CALMET meteorology. Results were generated for only 1990, so the minimum and maximum values for Cs/Cr, reflect variations seen over the receptor rings included in the range.

		2-m Source		35-m Source		200-m Source	
1-Hour	Range	Min	Max	Min	Max	Min	Max
	1-5 km	3.60	6.79	2.66	4.09	1.20	2.20
	10-50 km	1.39	3.90	1.21	3.43	1.01	1.67
	75-300 km	1.32	2.76	0.94	2.63	0.45	1.04
3-Hour	1-5 km	2.05	3.68	1.54	1.97	0.59	1.31
	10-50 km	1.63	3.77	0.96	1.72	0.96	2.06
	75-300 km	1.21	3.47	0.83	2.26	0.34	0.62
24-Hour	1-5 km	0.93	2.38	0.98	1.06	0.30	0.74
	10-50 km	2.32	2.79	0.78	1.35	0.72	1.38
	75-300 km	1.50	4.50	0.90	1.58	0.31	0.68
Annual	1-5 km	1.41	1.51	1.54	1.90	0.80	1.39
	10-50 km	1.61	2.05	1.54	1.87	1.11	1.37
	75-300 km	1.98	4.07	1.38	2.63	0.81	1.27

4.8.6 $SO_4^=$ deposition

Table 13 summarizes the maximum and minimum value seen for Cs/Cr, where Cs is the maximum sulfate deposition seen for 1990 along a receptor ring for a particular source and averaging time using the CALPUFF with ISC meteorology, and Cr is the maximum sulfate deposition seen along the same arc resulting from using the CALPUFF with fully developed CALMET meteorology. In each of the three ranges in Table 13, instances can be found where the screening estimate of sulfate deposition, Cs, is not as high as that obtained from the refined analysis, Cr. For sulfate deposition, the annual or seasonal average deposition is of most interest. For the lower release heights of 2-m and 35-m, the maximum annual sulfate deposition obtained with CALPUFF using ISC meteorology are consistently greater than were obtained for this site in 1990 using CALPUFF with CALMET meteorological data. For the 200-m

release, the CALPUFF screening estimates of sulfate deposition are generally higher than those obtained using CALPUFF with CALMET meteorology.

4.8.7 Old screen versus new screen estimates

Ambient SO_2 concentrations

In Section 4.7, it was shown that when both CALPUFF and ISC use the ISC meteorology with assumed flat terrain, there was for these comparisons a clear tendency for CALPUFF to develop higher maximum concentration estimates the ISC for all averaging times and for all distances downwind. Whether this will happen for a particular source-receptor pairing, is dependent on whether calms and wind reversal are existent in the proper sequence. The more frequently calm conditions occur for a site, the more likely CALPUFF can develop higher concentration impacts. It is concluded from comparisons results as summarized in Section 4.7 that it would be a misconception to consider the Level I screening estimates for ambient SO_2 concentration values as being overly conservative (i.e., too high). CALPUFF is capable of providing higher SO_2 concentration values than ISC simply due to the fact that calms and wind reversals are not ignored.

Ambient sulfate concentrations

In the IWAQM Phase 1 and Phase 2 recommendations, ambient sulfate concentrations are used in assessing long-range transport haze impacts. And in this context, the 24-hour averages are used (as explained in Section 3) to address the 'regional' nature of the haze assessment. In the Phase 1 recommendations, the screening estimate (Level 1) of sulfate concentration was obtained by multiplying the SO_2 concentration by 1.5 (to account for the difference in molecular weight between $SO_4^{=}$ and SO_2).

Shown in Figure 20 is a comparison of the 24-hr maximum sulfate concentrations derived using the Phase 1 screening procedure and using CALMET meteorology as input to CALPUFF. The Phase 1 screening procedure is seen to be considerably higher (on the order of 30 times higher) than that derived using CALPUFF. For the 200-m source, The Level 1 screening estimates are seen to be higher than that derived using CALPUFF for receptor rings of 50-km or less. Beyond 50-km, the Level 1 24-hr sulfate concentration estimates are similar to that derived using CALPUFF.

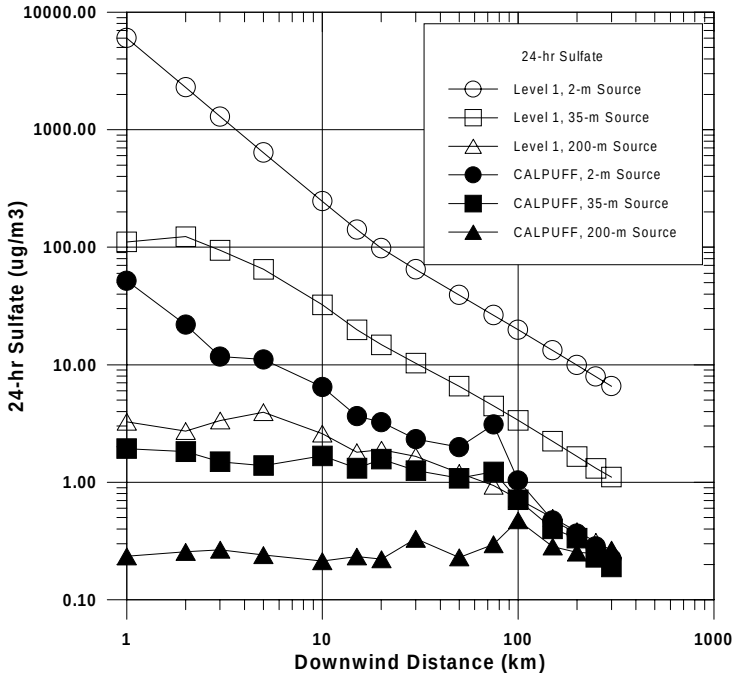

Figure 20. Comparison of Phase 1 Level 1 screening estimates of maximum 24-hour ambient sulfate concentrations versus maximum 24-hour ambient sulfate concentration derived using CALMET meteorology as input to CALPUFF.

Total sulfur deposition

In the IWAQM Phase 1 and Phase 2 recommendations, sulfur deposition is used in assessing air quality related values associated with forest health. In this context, the seasonal or annual averages are used (as explained in Section 3). In the Phase 1 recommendations, the screening estimate (Level 1) of total sulfur deposition flux was obtained by multiplying the SO_2 concentration by an assumed deposition velocity of 0.005 m/s, which was then multiplied by 0.5, since each gram of SO_2 deposited contributes 0.5 grams of sulfur. In the Phase 1 screening estimates, the sulfur deposition was assumed to be mostly from SO_2 gaseous deposition. In CALPUFF we can simulate the dry deposition of both SO_2 and sulfate. The total sulfur flux is then computed as 0.5 times the SO_2 deposition flux plus 0.33 times the $SO_4^=$ deposition flux (to account for amount of sulfur provided by $SO_4^=$ and SO_2).

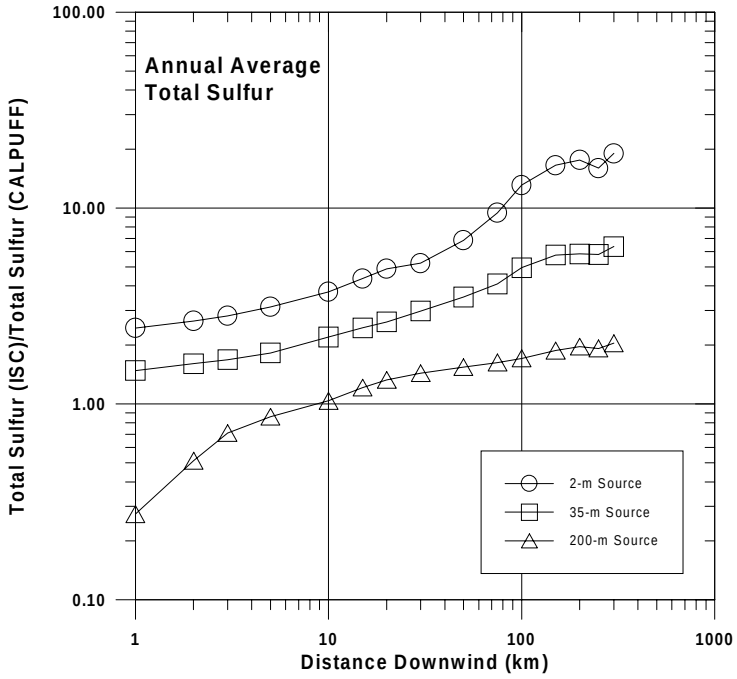

Figure 21. Comparison of annual average total sulfur flux as derived using the Phase 1 Level screening procedure and using CALMET as input to CALPUFF. Shown in the figure is the ratio formed by dividing the Level 1 result by the CALPUFF result.

Shown in Figure 21 is a comparison of the annual average total sulfur flux, derived using the Phase 1 Level 1 screening procedure and using CALMET as input to CALPUFF. In Figure 21, the comparison is shown by dividing the Phase 1 screening estimate by the CALPUFF result. For the more distant receptor rings, the Phase 1 screening procedure is seen to provide higher (by a factor of 2 to more than a factor of 10 times higher) than that derived using CALPUFF.

4.8.8 Findings and conclusions

In this section, we have summarized the results from a study in which a methodology was tested whereby CALPUFF was used with a simplified set of meteorological data, for the purpose of providing screening estimates of concentration and deposition impacts. It was seen that there were reasonably large variations in the SO_2 concentration maxima from one year to the next. There are limitations to the conclusions that can be reached, due to the limited nature of the testing that has been thus far accomplished. Comparisons of results obtained using the new screening methodology versus results obtained using fully developed CALMET meteorology has only been conducted for one location and for one year. In all cases examined, cases could be found where the CALPUFF screening results underestimated the maximum impacts simulated using more fully developed (CALMET) meteorology as input to CALPUFF. Thus IWAQM concludes that the screening method that has been tested

does not guarantee that the pollutant impacts will always be greater than that obtained using refined meteorology. Whether this precludes its use is a judgement decision. There is a certain degree of conservatism inherent in the screening procedure tested. This arises because the screening procedure requires use of receptor rings that completely surround the source being assessed, and it requires use of the maximum impact found anywhere along the receptor ring. In an actual situation, it is unlikely that the Class I area will completely surround the source being analyzed. It is more likely that the actual Class I area is limited to a small segment of a receptor ring. Thus if actual refined (fully developed) meteorology were developed and used, with actual source locations and receptors limited to the Class I area, one is likely to find the impacts simulated within the Class I may be considerably lower than that derived from the screening procedure for receptors that encircle the source.

4.9 CALMET/CALPUFF Enhancements

4.9.1 Use of *FDDA-MM* data with CALMET

Results of an ongoing investigation were reported by Sherwell and Garrison (1997). The study was being conducted by the Maryland Department of Natural Resources Power Plant Research Program (PPRP), in cooperation with EPA, to investigate the results that might be obtained using the CALMET/CALPUFF modeling system to simulate the magnitudes, sources, and possible reductions of NOx deposition to the Chesapeake Bay. In this study, the Penn State MM4 gridded 1990 meteorology data (discussed in Section 4.4) were employed. The EPA 1990 National Emissions Inventory for NOx has been used to derive source inputs. In the presentation by Sherwell and Garrison (1997), an overview was presented of the experiences gained in preparing and running the CALMET/CALPUFF system, and on the preliminary results of the analysis of NOx deposition to the Chesapeake Bay. A large part of their effort was developing the NOx inventory, due to its sheer size, as the raw inventory contained almost 90,000 entries for point sources and over 1100 counties in the defined domain.

The selection of their modeling domain was guided in part by a desire to compare results obtained using the CALMET/CALPUFF modeling system with those available from modeling runs from the Regional Acid Deposition Model (RADM). The RADM contains a more detailed treatment of the atmospheric chemical transformations and removal processes, and thus provides an interesting ‘check’ of the CALMET/CALPUFF modeling results. The final domain selected extended west through Illinois, north almost to the northern border of New York, south through most of

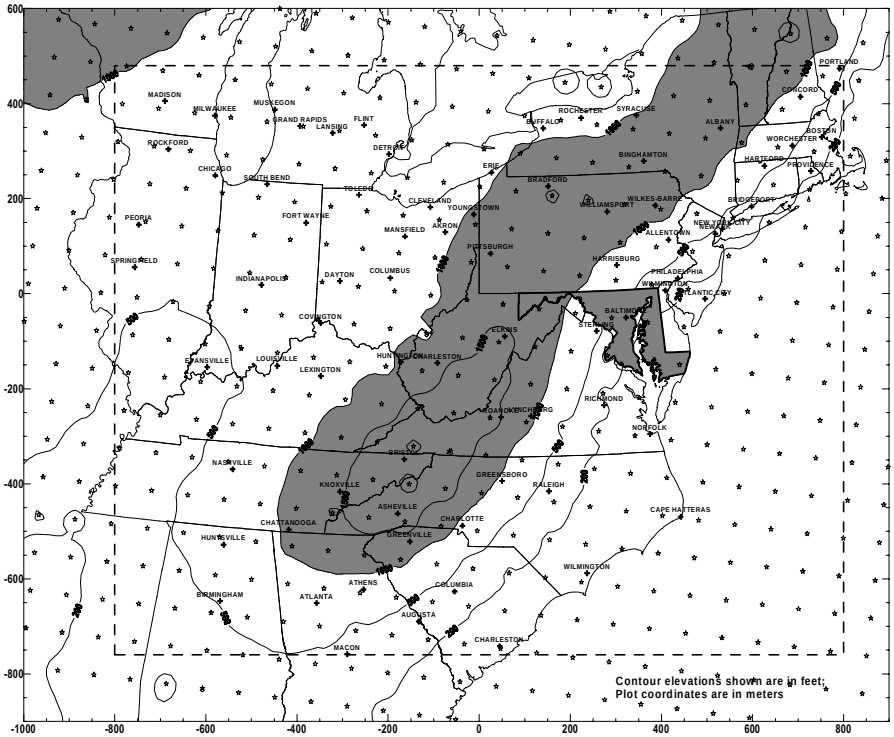

Figure 22. CALMET computational domain.

South Carolina, and covers most of southern New England (Figure 22). The MM4 data has a grid interval of 80 km. CALMET was used to produce 40 km gridded wind and meteorological fields. The fields had seven layers in the vertical: 10, 50, 150, 300, 750, 1500 and 3000 meters. Precipitation data were derived from the stations available on the Samson CD-ROM obtained from the National Climatic Data Center. Given the large computational domain, a lambert conformal projection scheme was selected. Figure 22 shows the location of the MM4 profile points throughout the domain, contours of terrain elevations based on the MM4 grid points, and the locations of the surface stations from which precipitation measurements were obtained and used.

To reduce the CALPUFF simulation times, a series of overlapping receptor grids were constructed, with the density of receptor increasing in the Chesapeake Bay area. The meteorological grid is displayed in Figure 22. The computation domain was sized to be somewhat larger than the domain of the sources being modeled. They had divided the source inventory into four ‘zones’, with zone 1 including sources within 50 km of the Chesapeake Bay, zone 2 including all sources out to 210 km, zone 3 including all sources out to 500, and zone 4 including all sources from 500 out to the edge of the domain shown in Figure 22. The CALPUFF simulations where configured to use the MESOPUFF II fine species chemical transformation scheme, and wet and

dry fluxes for HNO_3 and NO_3^- were calculated and stored. Constant background concentrations of ozone (80 ppb) and ammonia (10 ppb) were specified.

CALPUFF was run in one-month segments on a 200 MHZ Pentium Pro computer. Storage requirement per month were approximately 220 MB for the raw MM4 data for the selected domain, 75 MB for the CALMET output file used to drive CALPUFF, and 40 MB for the output files of wet and dry fluxes for two species (HNO_3 and NO_3^-). Each month took approximately 10 hours to run.

Total deposition due to dry and wet processes were roughly equal, with predicted wet deposition dominated by deposition of HNO_3 and dry deposition dominated by NO_3^-. On a domain-wide basis , the average total Nitrogen deposition rate was calculated to be about 3.64 kg/(hectare•year). This can be compared to the RADM results for 1990 (Dennis, 1997), which estimated the total Nitrogen deposition rate to be approximately 10 kg/hectare/year in the Chesapeake Bay area. In the most recent RADM simulations (R. Dennis, personal communication), the observations in the vicinity of the Chesapeake Bay and the current RADM seem to be in accord, with most of the wet and dry deposition resulting from HNO_3. In the Demonstration Assessment (Section 4.1), the low amount of wet deposition of HNO_3 estimated by CALPUFF was considered a surprise, given the high aqueous phase solubility of HNO_3. Given these more recent results and comparisons of RADM with observations, there is further cause to suspect the wet deposition results for HNO_3 to be underestimated by CALPUFF.

Of interest is that this analysis has in fact used the *FDDA-MM* meteorological data with the CALMET/CALPUFF modeling system successfully. They provide an independent check of the resources needed. The results are consistent with those found in performing the demonstration analyses, discussed in Section 4.1.

4.9.2 Use of CALMET to Develop Wind Fields

Scire and Robe (1997) reported on a series of enhancements to CALMET for improving the characterization of wind fields in the presence of topographical features that might be anticipated to induce strong upslope and downslope winds. Many industrial facilities are located in river valleys where the terrain effects can have a dominant influence on pollutant transport and dispersion. Furthermore, it is quite likely that the surface wind observations available may not be representative of the flow in the near vicinity of the facility (or conversely may only be representative in the near vicinity and not representative of flow conditions downwind). Attempting to resolve the fine-scale wind effects prognostic meteorological modeling is not only computationally demanding, but often beyond the state-of-the-art. CALMET uses diagnostic (empirical) models of these local-scale effects (upslope and downslope winds), which is computationally more cost-effective and provides a pragmatic solution to a complex problem.

The original wind field module in CALMET, was based on the parameterizations in the Diagnostic Wind Model (DWM) of Douglas and Kessler (1988). This module computed a slope flow (a vector oriented in the drainage direction) which was added to the initialized wind field components (Step 1 initialization). Time of day was used to deduce whether the slope flow was upwind or downwind. The magnitude of the slope flow was based on the local steepness of the terrain, the terrain elevation, the vertical temperature lapse rate, and the maximum terrain height within a radius of influence about the local point under consideration. An undesirable trait of this algorithm was that it would yield larger slope flows for higher terrain elevations, all other factors being equal. The original module used the ambient temperature lapse rate, whereas the potential temperature lapse rate provides the proper characterization of the static stability of the atmosphere. To address these concerns, a new downslope flow module was developed based on the shooting flow parameterization of Mahrt (1982) and a new upslope module was develop based on surface drag concepts. These new modules are no longer restricted to the first layer within CALMET, but instead can affect flow in upper layers.

The local sensible heat flux is an important parameter in deducing the magnitude and direction of the slope flows. This module in CALMET was upgraded to account for the angle of the terrain relative to the sun. For the sensible heat flux computations, the original algorithms assumed the terrain was horizontal to the earth. An east facing terrain slope will “feel” the effects of the sun’s heating in the morning and cooling in the afternoon sooner than a west facing terrain slope. To address this concern, algorithms by Whiteman and Allwine (1986) were added to CALMET that compute the solar radiation for a surface of arbitrary inclination and azimuth.

No matter how much skill is added in the computation of the slope flows, if the initial guess field in the Step 1 initialization is too far off, CALMET will poorly characterize the local wind flows. To address this concern, two enhancements were added to CALMET. First, instead of relying on only the upper-air observations to characterize the local vertical temperature profiles, an option was added to CALMET that allows the vertical temperature profiles using similarity theory (van Ulden and Holtslag, 1985). Second, a modification was added to CALMET that allows the user to control the influence of the upper-air observations and local surface observations in the construction of the Step 1 initialization wind fields. The user is allowed to specify height dependent factors, B, ranging from -1 (no influence by upper air observations) to +1 (no influence by surface observations). If the local surface observations are within the valley, they might be restricted to influencing the Step 1 initialization only for heights below the top of the valley, above which the upper-air observations could be given dominance.

Scire and Robe (1997) illustrated the enhancements discussed above by calculating wind fields in the Columbia River Valley. The region of interest included the City of Wenatchee, WA and the region to the southeast of the city. Wenatchee is located on both sides of the river and includes a relatively flat elevated plain. Figure 23

shows the CALMET modeling domain. The terrain variation is substantial, extending from under 200 meters elevations above mean sea level (MSL) to over 1700 meters MSL at the higher peaks in the southwest part of the domain. The Columbia River runs to the southeast, turns roughly east, and then turns again to the south over a distance of 20 kilometers. The high terrain features change orientation from east-west to north-south in the southern part of the domain.

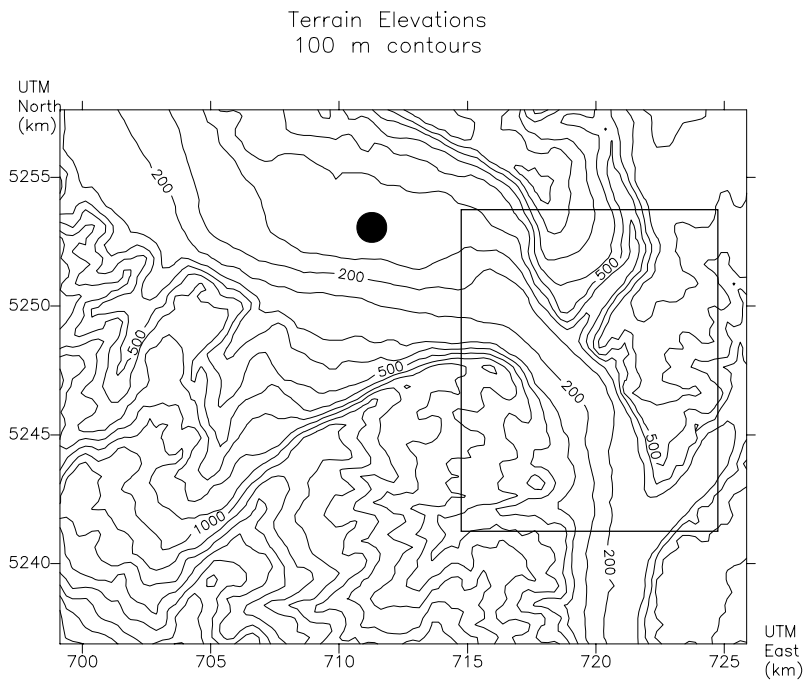

Figure 23. Terrain contours for the Wenachee, WA domain. Contour internal is 100 m, and the location of the Wenatchee (Pangborn) Airport is indicated by the filled circle. The box inset shows the subdomain for which slope flows are presented.

To characterize the terrain, a grid resolution of 250 meters was used in CALMET. The modeling domain consisted of 108 by 84 horizontal grid cells. Nine levels were used in the vertical: 10, 50, 120, 230, 450, 800, 1250 and 2600 meters above ground. The lower four levels are within the valley, the upper three levels are above most of the terrain features. The local wind observations were available at the location shown with a filled circle in Figure 23. This location is within the valley, and the wind rose for the location shows the influence for the local winds to channel and align with the local orientation of the valley. The height dependent factors, B, were set at -1, -1, -1, -1, +0.5, +0.8, +1, +1, +1. The nearest upper air observation station is Spokane, WA, which is over 200 km to the east of the CALMET domain.

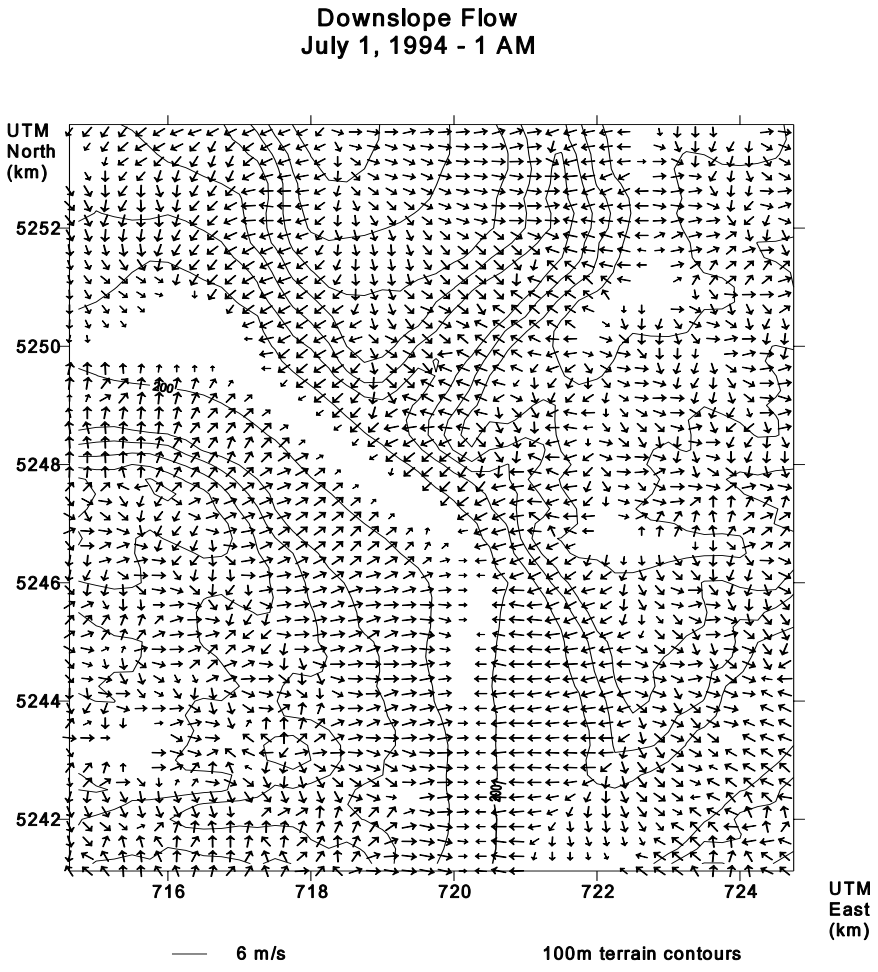

Figure 24. Down slope flow components for 1:00 AM July 1, 1994 for Wenatchee, WA . Wind vectors are plotted every 500 meters (at every second grid point).

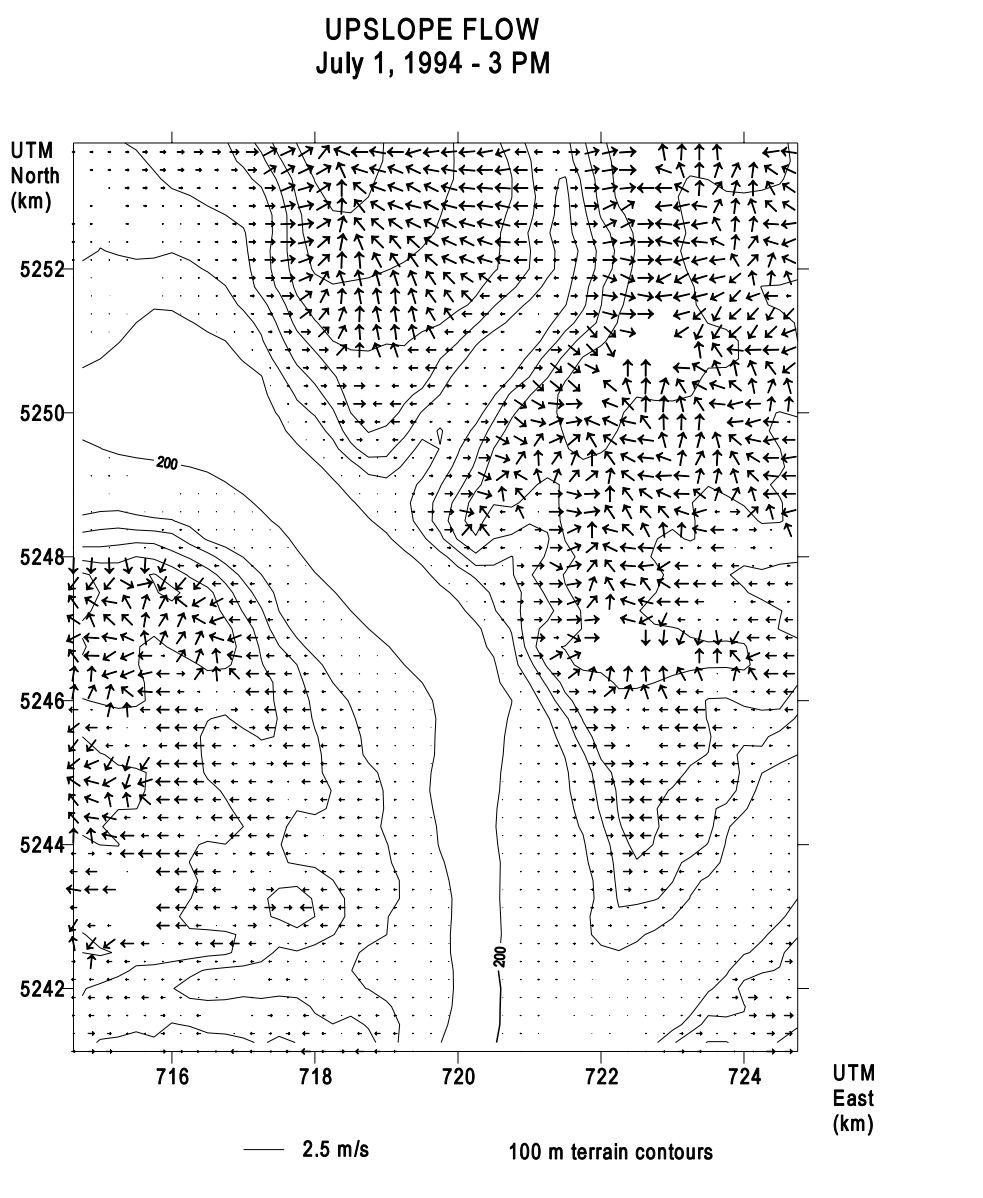

Figure 25. Upslope flow components for 3:00 PM July 1, 1994 for Wenatchee, WA . Wind vectors are plotted every 500 meters (at every second grid point).

Figure 24 shows the computed CALMET layer 1 downslope flows and Figure 25 shows the computed CALMET layer 1 upslope flows. The region shown in these figures is the box inset of Figure 23. The moderately strong nighttime drainage flows (1:00 AM, July 1, 1994) are shown in Figure 24. Figure 25 shows the computed upslope flows, which are (as expected) weaker than the downslope flows. Upslope flows are not expected to accelerate as rapidly as downslope flows.

The pattern and magnitude of the CALMET winds were considered consistent with expectations. These winds were developed using a single surface station in the valley and an upper air station located well outside of the valley. The computed wind fields show the expected diurnal cycle of nighttime drainage followed by daytime upslope flows. The patterns are consistent with the strong terrain channeling of the main valley and within the smaller side canyons. These wind fields would be expected to better characterize the transport of the pollutants. It was anticipated that the proper characterization of the local terrain influences on the wind field would provide a more realistic characterization of the transport around major terrain features rather than directly impacting apon such features.

These results are relevant to the Phase 2 recommendations. They demonstrate that realistic wind fields can be produced using diagnostic techniques. They illustrate that in some situations, the proper characterization of the terrain's influence on the wind fields will require gridded terrain heights, with a grid resolution of order 250 m. This would not be expected for resolving transport and dispersion of plumes that have already traveled large distances and are already quite broad relative to the local terrain features. But it is reasonable to expect that sources within such terrain would require more care to be taken in the characterization of the wind fields, otherwise the transport and resulting dispersion would be poorly characterized. These results also illustrate the feasibility of performing local-scale impacts assessments of the transport and dispersion of emissions from sources located in severe terrain, even when available meteorological observations are sparse.

4.9.3 Kincaid SF_6 and Lovett SO_2 Comparisons

The goal of this study (Strimaitis et al., 1997) was to conduct an evaluation of CALPUFF in comparison with ISCST3 (U.S. EPA, 1995c) for the Kincaid data set, and CTDMPLUS (Perry et al., 1989) for the Lovett data set. Also, enhancements were tested in a special version of CALPUFF (4.07), in which convective scaling parameterizations and concepts were implemented to better characterize dispersion from tall stacks during unstable conditions. Earlier versions of CALPUFF use a simple Gaussian distribution to characterize the vertical distribution of puff material within the convective boundary layer (CBL). As the puff grew, it soon filled the layer between the ground and the mixing height, resulting in a uniform vertical distribution. Within this framework, the primary effect of the convective motions in the mixed layer was to cause a rapid growth in the vertical size of a puff. Depending on the CALPUFF dispersion option selected, this growth rate is either parameterized by the stability class, scaled by measured turbulence intensity, or scaled by a turbulence intensity computed from the surface layer parameters.

In the last decade, modeling techniques that recognize the asymmetry of the vertical dispersion process in the CBL have matured. These techniques explicitly account for the differences between the distribution and strength of updrafts and downdrafts in the layer as they relate to the ensemble-mean concentration distribution.

One such technique that is simple yet effective is the “p.d.f.” approach that relates the probability density function of the vertical position of puff mass in the layer to the skewed probability density function of vertical velocity. Using the superposition of two Gaussian distributions to characterize the skewed p.d.f of the vertical velocity, the p.d.f. model produces a “dual plume” formulation that maps the evolution of one plume that is initially carried toward the ground in a (mean) downdraft, and a second plume that initially rises toward the top of the mixed layer in a (mean) updraft. Subsequent “reflections” from both the ground and the lid are simulated using image sources. Because each of these plumes has its own mean vertical velocity and rate of spread, the resulting vertical distribution of mass is skewed in much the same way as the observed distributions. The initial downdraft plume is called the direct source because it travels directly from an elevated source (accounting for the plume rise velocity) to the ground, while the initial updraft plume is called the indirect source because it reaches the ground only after traversing the full depth of the mixed layer.

U.S. EPA (1995d) extended the p.d.f. CBL formulation to include a simple way of simulating the tendency of highly buoyant plumes to “loft” at the top of the mixed layer, remaining there for some time before the convective eddies are able to overcome the buoyancy and mix their mass to the surface. This formulation forms the basis of the CBL component of AERMOD, U.S. EPA (1995d), and has been adapted for use in CALPUFF (4.07). Strimaitis et al. (1997) adopted AERMOD’s CBL parameterizations for obtaining the mean updraft and downdraft properties, and also their novel simulation of the lofting plume by means of the effective rise of the indirect source. However, the CALPUFF algorithms for treating partial penetration and subsequent entrainment into the mixed layer as the layer grows remain unchanged.

The Kincaid Generating Station is a coal-fired electric generating station with two 606 megawatt (MW) units vented through a single 187 meter stack. It is located in Kincaid, Illinois, approximately 25 kilometers southeast of Springfield. The power plant is in an area of relatively flat terrain surrounded by farmland. As part of an intensive monitoring program sponsored by the Electric Power Research Institute (EPRI), SF_6 tracer was released as a gas continuously through the stack for approximately 30 experiments of 6-9 hours in length during 1980 and 1981. A network of 200 samplers located from 0.5 to 50 km from the stack measured hourly SF_6 concentrations at the ground level. The SF_6 samplers were located approximately in arcs at distances of 0.5, 1, 2, 3, 5, 7, 10, 15, 20, 30, 40, and 50 km from the stack. In addition to measurements of winds and turbulence made at four levels on a 100-m tower, other meteorological data collected include vertical profile data from balloons, solar and net radiation, and cloud cover.

In this study the meteorological data files were developed by emphasizing the tower winds and temperatures, the “observed” mixing heights, and by computing the surface layer parameters using the RAMMET (U.S. EPA, 1995e) preprocessor. One major element in preparing the data files for CALPUFF relates to the transport time from the stack to the outermost receptor arc, which is frequently greater than 1 hour.

While plume models neglect this feature of the study, puff models do not. The tracer gas was typically started 1 to 4 hours before the sampling network, so emissions during the initial transport period are known. Therefore, the full meteorological data set was used (not just the meteorological hours for when tracer data were available) to extract data for complete days (24 hours) for each of the tracer experiments. This allowed development of all of the data needed to properly simulate each period.

The Lovett Power Plant is located in the Hudson River Valley approximately 70 km north of New York City. The terrain in the area rises to approximately 330 meters above the stack base elevation along a ridge 2.5 km north of the stack. The highest point in the area is 340 meters above stack base at about 3 km north of the facility. SO_2 emissions were released from a 145 meter stack containing two flues. Hourly stack parameters (temperatures and flows) were derived from continuously reported load data. The monitoring period is one full year. Twelve continuous SO_2 monitors were located to the west, south, and north of the facility. Ten of the twelve monitors were located in complex terrain from 2 km to 3.5 km from the stack. These ten monitors were all located at or above the elevation of the stack top. Two monitors were located south of the facility at distances of 2 km and 8.5 km for purposes of estimating background concentrations.

Meteorological data were collected on a 100 meter tower located in the valley south-southwest of the stack. The tower was instrumented at three levels (10 m, 50 m, and 100 m). Wind speed, wind direction, and horizontal turbulence (σ_θ) were measured at all three levels. In addition, four 10 meter meteorological towers collecting wind speed, wind direction and σ_θ were located in an arc on the high terrain to the west, west-northwest, north-northwest, and north of the stack. Much of the data needed to apply CALPUFF to this site was prepared by Paumier et al. (1992) for their evaluation of CTDMPLUS. These data files were used in this evaluation, and all but the hourly emissions data could be applied directly to CALPUFF.

For the Kincaid data, quality indicators of 1, 2, and 3 had been assigned to the data. A quality indicator of 1 meant that sampling was very incomplete and no maximum concentration could reliably be determined for the arc. A quality indicator of 3 meant that a distinct pattern could be seen in the data for the arc, and a maximum concentration could be determined reliably. Model performance results for the Kincaid data set were presented for two subsets of the data. The first were comprised of all arc-hours for which the peak concentration on the arc was given a quality indicator (QI) of 2 or 3; the second was the subset of these arc-hours with a QI of 3.

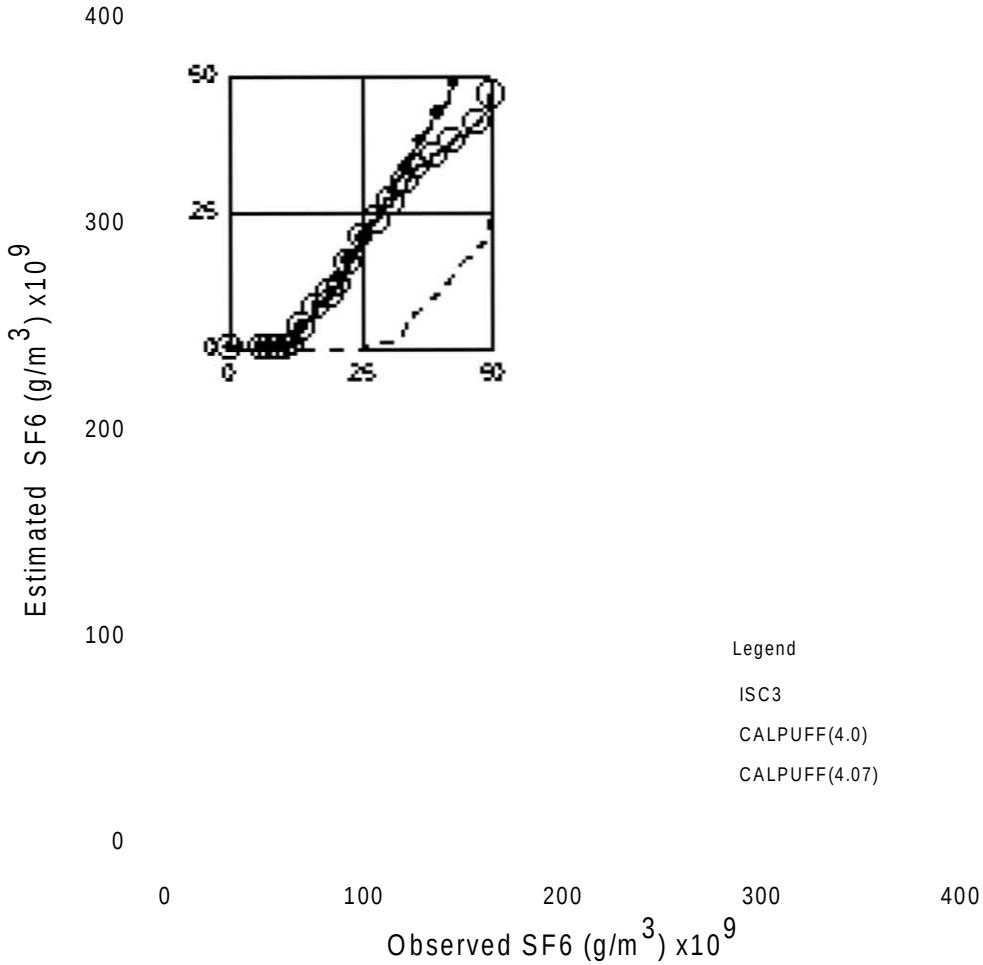

Figure 26. Q-Q plots for Kincaid, comparing observed surface concentration values of SF_6 with simulation results by CALPUFF(4.0), CALPUFF(4.07) and ISC3 for Quality 2 and 3 data.

Figure 26 shows the Quantile-Quantile (Q-Q) plots for CALPUFF(4.07), CALPUFF(4.0) and ISCST3 compared to the observations, for data of quality 2 and 3. Although all models display a tendency to predict more zero-impacts (see inset) than is observed, both versions of CALPUFF predict fewer zeros than ISCST3. This is traceable to the fact that for all CALPUFF model runs, the option for partial plume penetration was enabled. ISC3 sets all surface concentrations to zero whenever the computed centerline of the plume is detected to be above the mixing height. CALPUFF would do the same, except when the partial plume penetration option is enabled. When this option is enabled, a computation is made based on the size of the dispersing plume, and any mass below the mixing height is allowed to continue to disperse and possibly impact surface receptors. While fewer observed concentrations are underpredicted by both versions of CALPUFF (106 out of 586 values) than are

underpredicted by ISCST3 (236 out of 586 values), there remains a substantial number of large observed concentrations for which both models miss (zero is predicted)

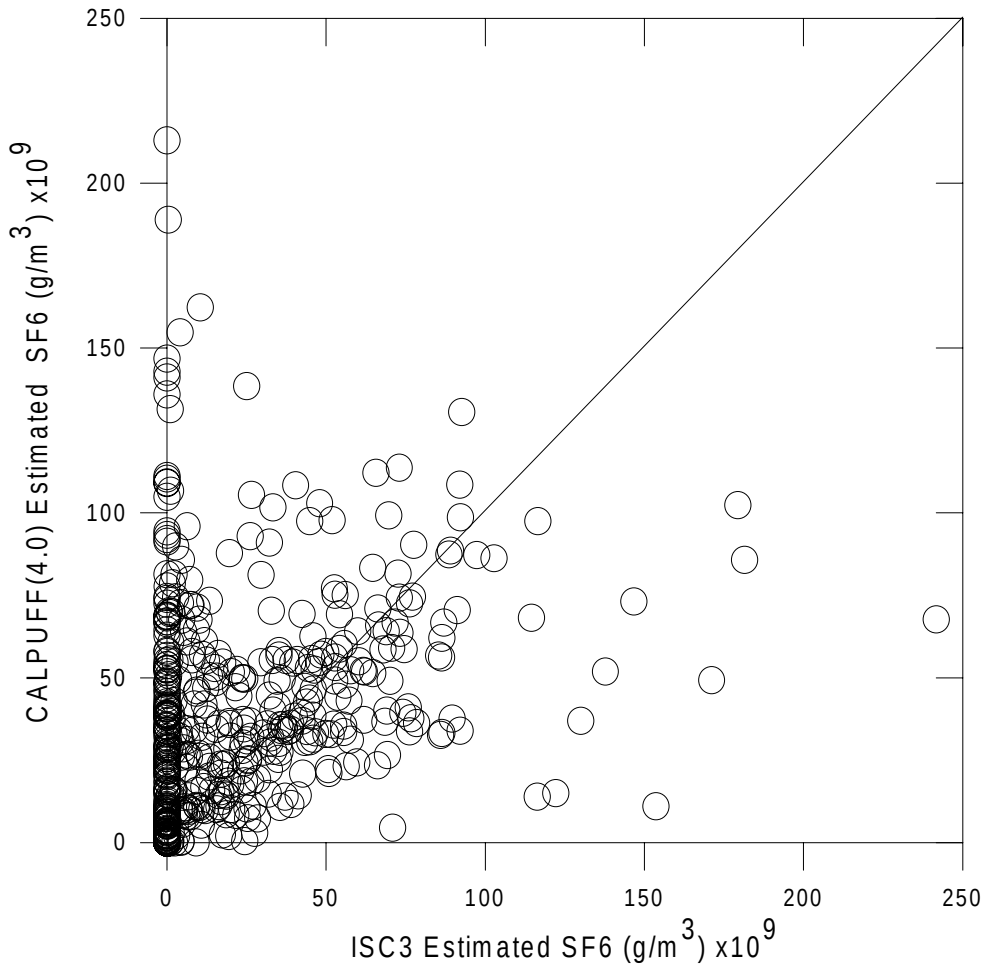

Figure 27. Scatter plot for Kincaid, comparing CALPUFF(4.0) and ISC3 simulation results for surface concentration values of SF_6 for Quality 2 and 3 data.

The CALPUFF(4.0) results in Figure 26 appear to be similar to the ISC3 results. This is true in the sense that the computed maxima are of a similar value. But the CALPUFF(4.0) runs were conducted using dispersion parameters based on similarity theory, and a scatter plot of CALPUFF(4.0) versus ISC3, Figure 27, reveals that the two models are not providing as similar of results as might be deduced from inspection of Figure 26.

CALPUFF(4.07) is seen to overpredict the upper range of observed concentrations, while CALPUFF(4.0) and ISCST3 underpredict throughout, and the ranked distribution for CALPUFF(4.07) lies nearer the 1:1 line in Figure 26. How much of this improved performance might be attributed to the p.d.f. algorithms for the CBL?

As can be seen in Figure 26, the lower end of the ranked distributions for both versions of CALPUFF appear to coincide, which implies that reasons for the elevated frequency of zero-impact predictions are not related to the treatment of dispersion in the CBL. The character of the higher end is quite different, with CALPUFF(4.0) producing concentrations more like ISCST3 than CALPUFF(4.07). This suggests that the p.d.f. is responsible for the improvements at the high end noted in Figure 26.

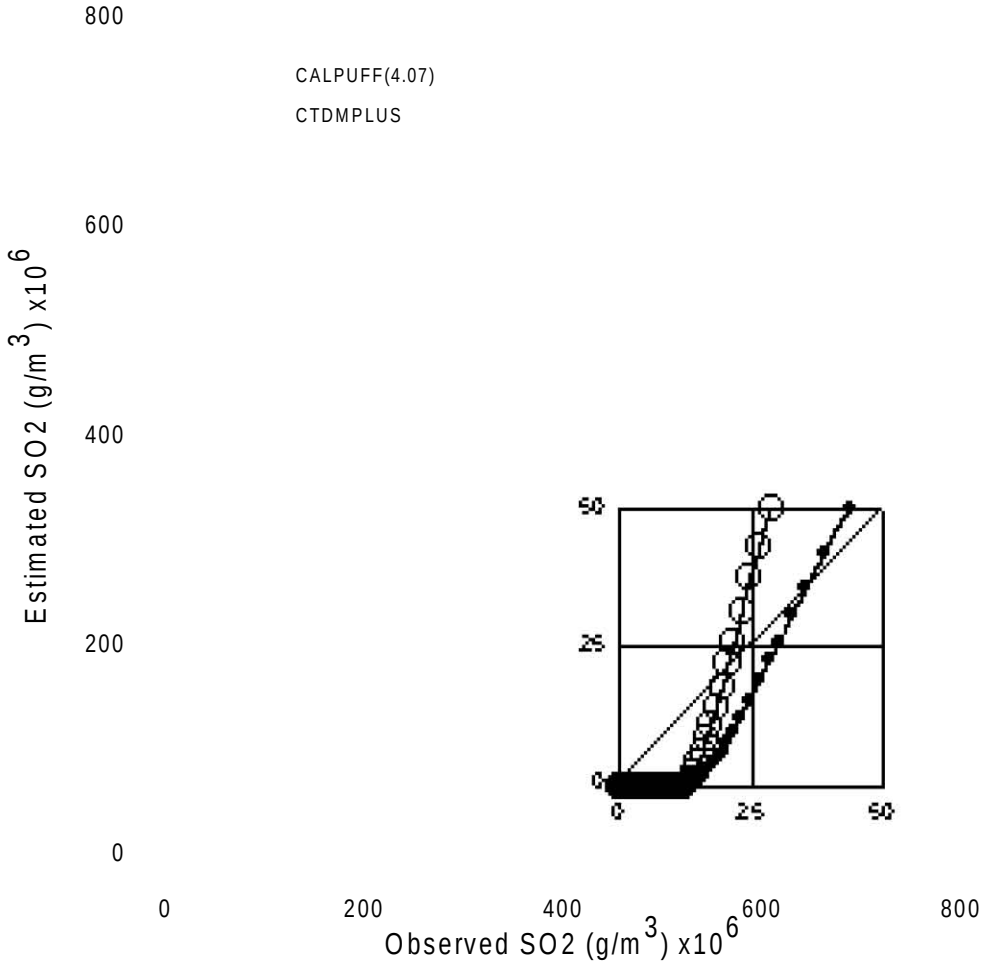

Figure 28. Q-Q plots for Lovett, comparing observed surface concentration values of SO_2 with simulation results CALPUFF(4.07) and CTDMPLUS

For the Lovett data set, Paumier et al. (1992) found that CTDMPLUS and RTDM predictions were poorly correlated with the observed peak hourly concentrations. Given that CALPUFF was applied with the same meteorological data, similar results were expected and found. Figure 28 shows the Q-Q plot for CALPUFF(4.07) and CTDMPLUS compared to the observations. Although both models tend to overpredict the observed ranked distribution, CALPUFF predictions lie nearer the 1:1 line. The

dashed line in Figure 28 indicates an overprediction of two, which is close to the results depicted for CTDMPLUS.

The evaluation results presented suggests that the p.d.f. formulations tested in CALPUFF(4.07) eliminates the tendency seen in the CALPUFF(4.0) and ISC3 to underestimate the surface concentration values for the Kincaid data set, and CALPUFF(4.07) overpredicts surface concentration values less than CTDMPLUS for the Lovett data set. Correlation of hourly predicted and observed concentrations for the Lovett data set are poor for both CALPUFF(4.07) and CTDMPLUS, suggesting that more diagnostic analyses of this data set may be fruitful. For the Kincaid data, CALPUFF (4.0) performance is similar to ISC3's. And for the Kincaid evaluation, performance during periods with observed mixing heights less that about 600m suggests that more mass remains in the mixed layer than is predicted by the models, even with partial penetration enabled.

5.0 CONCLUSIONS

This report provides a summary and status report of the activities sponsored and initiated by the Interagency Workgroup on Air Quality Modeling (IWAQM). The IWAQM was formed to provide a focus for development of air quality models for assessment of pollutant source impacts on Federal Class I areas and wilderness areas. In particular, IWAQM has focused attention on providing modeling techniques for assessing possible adverse air quality impacts resulting from long-range transport of pollutants, as required by the prevention of significant deterioration (PSD) program.

In 1993, IWAQM provided interim Phase 1 recommendations that provided the best approach from existing "off-the-shelf-techniques." The MESOPUFF II puff modeling system was recommended for use. This model provided the ability to simulate the influence of time and space varying meteorological conditions on transport and dispersion. It provided a first-order approximate characterization of the formation of sulfate and nitrate during transport downwind. It provided characterizations for the removal of pollutants by dry and wet deposition. The meteorology processing had limited capabilities, as it was not able to characterize geographical terrain slope flows. The puff dispersion model had no capabilities to address effects associated with variation of terrain heights. Furthermore, due to limitations in the dispersion treatments, the puff model was not considered appropriate for use in characterizing impacts associated with transport distances of less than 50 km.

As discussed in Appendix D, IWAQM provided a status report of ongoing activities at the Sixth Modeling Conference, which was held in Washington, D.C. August 9-10, 1995. As a result of comments received, a series of investigations were undertaken. Comparisons were made of CALPUFF simulated dispersion with near-surface concentrations collected during several tracer field studies, where the transport distances were of the order 50 to 300 km. Comparisons were made of CALPUFF simulated dispersion with simulation results obtained using the Industrial Source Complex (ISC3) plume dispersion model. Initially, the focus was on whether CALPUFF and ISC3 gave similar results for steady-state meteorological conditions. Once this was confirmed, the focus shifted to investigating what difference might result between a puff and plume model, having identical meteorology and dispersion. It became clear that wind reversals and buildup of pollutant mass during calm wind conditions could result in large differences in simulation results. As a consequence of comments received and of the puff/plume model comparisons, a new screening analysis was tested that relied on use of the CALPUFF dispersion model with a greatly simplified characterization of the hourly meteorological conditions.

Based on the findings of the various investigations summarized in Section 4, IWAQM is providing a Phase 2 recommendation to replace the interim Phase 1 recommendation. The CALPUFF modeling system is recommended in place of the MESOPUFF II modeling system for a number of reasons. A primary consideration is that the CALMET meteorological processor is capable of diagnostically characterizing

geographic terrain slope flows, and has been updated to allow use of sophisticated output from modern mesoscale meteorological processors. Another important consideration is that the CALPUFF puff dispersion algorithms have been fashioned to allow characterization of both local-scale and long-range transport and dispersion. This allows use of one model for all sources with a consistent treatment of the chemistry and fate of the pollutants. Using CALPUFF within the new screening analysis provides consistent treatment of the chemistry and fate, and some of the 'causality' effects of hourly varying meteorology that a puff dispersion model can treat more directly and easily than a standard plume dispersion model.

This Phase 2 recommendation provides a major improvement in the treatment and characterization of the meteorological conditions and the mesoscale transport. There is yet room for improvement in the characterization of the chemistry and fate of the pollutants. The CALPUFF dispersion model represents a major improvement over the MESOPUFF II model in its flexibility for treating a variety of source types, time varying emission rates, and of dispersion situations. The IWAQM recommends the CALPUFF modeling system for use as a refined long-range transport and dispersion modeling technique for characterizing reasonably attributable pollutant impacts from one or a few sources.

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APPENDIX A
CALMET RECOMMENDATIONS

In the following, a listing is provided of the defaults currently assumed in CALMET for long-range transport analyses in involving assessments of not on concentration impacts, but also deposition flux impacts and visibility impacts. Some of the variables have the 'Value' is listed in bold. This is meant to indicate that these likely will need to be tailored for a given application.

Variable	Description	Value
GEO.DAT	Name of Geophysical data file	GEO.DAT
SURF.DAT	Name of Surface data file	SURF.DAT
PRECIP.DAT	Name of Precipitation data file	PRECIP.DAT
NUSTA	Number of upper air data sites	User Defined
UPn.DAT	Names of NUSTA upper air data files	UPn.DAT
IBYR	Beginning year	User Defines
IBMO	Beginning month	User Defines
IBDY	Beginning day	User Defines
IBHR	Beginning hour	User Defines
IBTZ	Base time zone	User Defines
IRLG	Number of hours to simulate	User Defines
IRTYPE	Output file type to create (must be 1 for CALPUFF)	1
LCALGRD	Are w-components and temperature needed?	T
NX	Number of east-west grid cells	**User Defines**
NY	Number of north-south grid cells	**User Defines**
DGRIDKM	Grid spacing	**User Defines**
XORIGKM	Southwest grid cell X coordinate	User Defines
YORIGKM	Southwest grid cell Y coordinate	User Defines
XLAT0	Southwest grid cell latitude	User Defines
YLON0	Southwest grid cell longitude	User Defines
IUTMZN	UTM Zone	User Defines
LLCONF	When using Lambert Conformal map coordinates, rotate winds from true north to map north?	F
XLAT1	Latitude of 1st standard parallel	**30**
XLAT2	Latitude of 2nd standard parallel	**60**

Variable	Description	Value
RLON0	Longitude used if LLCONF = T	**90**
RLAT0	Latitude used if LLCONF = T	**40**
NZ	Number of vertical layers	**User Defines**
ZFACE	Vertical cell face heights (NZ+1 values)	**User Defines**
LSAVE	Save met. data fields in an unformatted file?	T
IFORMO	Format of unformatted file (1 for CALPUFF)	1
NSSTA	Number of stations in SURF.DAT file	User Defines
NPSTA	Number of stations in PRECIP.DAT	User Defines
ICLOUD	Is cloud data to be input as gridded fields? (0 = No)	0
IFORMS	Format of surface data (2 = formatted)	2
IFORMP	Format of precipitation data (2 = formatted)	2
IFORMC	Format of cloud data (2 = formatted)	2
IWFCOD	Generate winds by diagnostic wind module? (1 = Yes)	1
IFRADJ	Adjust winds using Froude number effects? (1 = Yes)	1
IKINE	Adjust winds using kinematic effects? (1 = Yes)	0
IOBR	Use O'Brien procedure for vertical winds? (0 = No)	0
ISLOPE	Compute slope flows? (1 = Yes)	1
IEXTRP	Extrapolate surface winds to upper layers? (-4 = use similarity theory and ignore layer 1 of upper air station data)	-4
ICALM	Extrapolate surface calms to upper layers? (0 = No)	0
BIAS	Surface/upper-air weighting factors (NZ values)	NZ*0

Variable	Description	Value
IPROG	Using prognostic or MM-FDDA data? (0 = No)	0
LVARY	Use varying radius to develop surface winds?	**F**
RMAX1	Max surface over-land extrapolation radius (km)	**User Defines**
RMAX2	Max aloft over-land extrapolation radius (km)	**User Defines**
RMAX3	Maximum over-water extrapolation radius (km)	**User Defines**
RMIN	Minimum extrapolation radius (km)	0.1
RMIN2	Distance (km) around an upper air site where vertical extrapolation is excluded (Set to -1 if IEXTRP = ±4)	4
TERRAD	Radius of influence of terrain features (km)	**User Defined**
R1	Relative weight at surface of Step 1 field and obs	**User Defines**
R2	Relative weight aloft of Step 1 field and obs	**User Defines**
DIVLIM	Maximum acceptable divergence	5.E-6
NITER	Max number of passes in divergence minimization	50
NSMTH	Number of passes in smoothing (NZ values)	2, 4*(NZ-1)
NINTR2	Max number of stations for interpolations (NA values)	**99**
CRITFN	Critical Froude number	1
ALPHA	Empirical factor triggering kinematic effects	0.1
IDIOPT1	Compute temperatures from observations (0 = True)	0
ISURFT	Surface station to use for surface temperature (between 1 and NSSTA)	**User Defines**
IDIOPT2	Compute domain-average lapse rates? (0 = True)	0
IUPT	Station for lapse rates (between 1 and NUSTA)	**User Defines**
ZUPT	Depth of domain-average lapse rate (m)	200

Variable	Description	Value
IDIOPT3	Compute internally inital guess winds? (0 = True)	0
IUPWND	Upper air station for domain winds (-1 = 1/r**2 interpolation of all stations)	-1
ZUPWND	Bottom and top of layer for 1st guess winds (m)	1, 1000
IDIOPT4	Read surface winds from SURF.DAT? (0 = True)	0
IDIOPT5	Read aloft winds from UPn.DAT? (0 = True)	0
CONSTB	Neutral mixing height B constant	1.41
CONSTE	Convective mixing height E constant	0.15
CONSTN	Stable mixing height N constant	2400
CONSTW	Over-water mixing height W constant	0.16
FCORIOL	Absolute value of Coriolis parameter	1.E-4
IAVEXZI	Spatial averaging of mixing heights? (1 = True)	1
MNMDAV	Max averaging radius (number of grid cells)	1
HAFANG	Half-angle for looking upwind (degrees)	30
ILEVZI	Layer to use in upwind averaging (between 1 and NZ)	**1**
DPTMIN	Minimum capping potential temperature lapse rate	0.001
DZZI	Depth for computing capping lapse rate (m)	200
ZIMIN	Minimum over-land mixing height (m)	50
ZIMAX	Maximum over-land mixing height (m)	3000
ZIMINW	Minimum over-water mixing height (m)	50
ZIMAXW	Maximum over-water mixing heigh (m)	3000
IRAD	Form of temperature interpolation (1 = 1/r)	1
TRADKM	Radius of temperature interpolation (km)	500

Variable	Description	Value
NUMTS	Max number of stations in temperature interpolations	5
IAVET	Conduct spatial averaging of temperature? (1 = True)	1
TGDEFB	Default over-water mixed layer lapse rate (K/m)	-0.0098
TGDEFA	Default over-water capping lapse rate (K/m)	-0.0045
JWAT1	Beginning landuse type defining water	999
JWAT2	Ending landuse type defining water	999
NFLAGP	Method for precipitation interpolation (2 = 1/r**2)	2
SIGMAP	Precip radius for interpolations (km)	100
CUTP	Minimum cut off precip rate (mm/hr)	0.01
SSn	NSSTA input records for surface stations	User Defines
USn	NUSTA input records for upper-air stations	User Defines
PSn	NPSTA input records for precipitation stations	User Defines

APPENDIX B
CALPUFF RECOMMENDATIONS

In the following, a listing is provided of the defaults currently assumed in CALPUFF for long-range transport analyses in involving assessments of not on concentration impacts, but also deposition flux impacts and visibility impacts. Some of the variables have the 'Value' is listed in bold. This is meant to indicate that these likely will need to be tailored for a given application.

Variable	Description	Value
METDAT	CALMET input data filename	CALMET.DAT
PUFLST	Filename for general output from CALPUFF	CALPUFF.LST
CONDAT	Filename for output concentration data	CONC.DAT
DFDAT	Filename for output dry deposition fluxes	DFLX.DAT
WFDAT	Filename for output wet deposition fluxes	WFLX.DAT
VISDAT	Filename for output relative humidities (for visibility)	VISB.DAT
METRUN	Do we run all periods (1) or a subset (0)?	0
IBYR	Beginning year	User Defined
IBMO	Beginning month	User Defined
IBDY	Beginning day	User Defined
IBHR	Beginning hour	User Defined
IRLG	Length of run (hours)	User Defined
NSPEC	Number of species modeled (for MESOPUFF II chemistry)	5
NSE	Number of species emitted	3
MRESTART	Restart options (0 = no restart), allows splitting runs into smaller segments	**0**
METFM	Format of input meteorology (1 = CALMET)	1
AVET	Averaging time lateral dispersion parameters (minutes)	60
MGAUSS	Near-field vertical distribution (1 = Gaussian)	1
MCTADJ	Terrain adjustments to plume path (3 = Plume path)	**3**
MCTSG	Do we have subgrid hills? (0 = No), allows CTDM-like treatment for subgrid scale hills	**0**
MSLUG	Near-field puff treatment (0 = No slugs)	0

Variable	Description	Value
MTRANS	Model transitional plume rise? (1 = Yes)	1
MTIP	Treat stack tip downwash? (1 = Yes)	1
MSHEAR	Treat vertical wind shear? (0 = No)	0
MSPLIT	Allow puffs to split? (0 = No)	**0**
MCHEM	MESOPUFF-II Chemistry? (1 = Yes)	1
MWET	Model wet deposition? (1 = Yes)	1
MDRY	Model dry deposition? (1 = Yes)	1
MDISP	Method for dispersion coefficients (3 = PG & MP)	3
MTURBVW	Turbulence characterization? (Only if MDISP = 1 or 5)	3
MDISP2	Backup coefficients (Only if MDISP = 1 or 5)	3
MROUGH	Adjust PG for surface roughness? (0 = No)	0
MPARTL	Model partial plume penetration? (0 = No)	1
MTINV	Elevated inversion strength (0 = compute from data)	0
MPDF	Use PDF for convective dispersion? (0 = No)	0
MSGTIBL	Use TIBL module? (0 = No) allows treatment of subgrid scale coastal areas	0
MREG	Regulatory default checks? (1 = Yes)	1
CSPECn	Names of species modeled (for MESOPUFF II, must be SO2, SO4, NOX, HNO3, NO3)	**User Defined**
Specie Names	Manner species will be modeled	**User Defined**
Specie Groups	Grouping of species, if any.	**User Defined**
NX	Number of east-west grids of input meteorology	User Defined
NY	Number of north-south grids of input meteorology	User Defined
NZ	Number of vertical layers of input meteorology	User Defined

Variable	Description	Value
DGRIDKM	Meteorology grid spacing (km)	User Defined
ZFACE	Vertical cell face heights of input meteorology	User Defined
XORIGKM	Southwest corner (east-west) of input meteorology	User Defined
YORIGIM	Southwest corner (north-south) of input meteorology	User Defined
IUTMZN	UTM zone	User Defined
XLAT	Latitude of center of meteorology domain	User Defined
XLONG	Longitude of center of meteorology domain	User Defined
XTZ	Base time zone of input meteorology	User Defined
IBCOMP	Southwest X-index of computational domain	**User Defined**
JBCOMP	Southwest Y-index of computational domain	**User Defined**
IECOMP	Northeast X-index of computational domain	**User Defined**
JECOMP	Northeast Y-index of computational domain	**User Defined**
LSAMP	Use gridded receptors? (T = Yes)	F
IBSAMP	Southwest X-index of receptor grid	User Defined
JBSAMP	Southwest Y-index of receptor grid	User Defined
IESAMP	Northeast X-index of receptor grid	User Defined
JESAMP	Northeast Y-index of receptor grid	User Defined
MESHDN	Gridded recpetor spacing = DGRIDKM/MESHDN	1
ICON	Output concentrations? (1 = Yes)	1
IDRY	Output dry deposition flux? (1 = Yes)	1
IWET	Output west deposition flux? (1 = Yes)	1
IVIS	Output RH for visibility calculations (1 = Yes)	1
LCOMPRS	Use compression option in output? (T = Yes)	T

Variable	Description	Value
ICPRT	Print concentrations? (0 = No)	0
IDPRT	Print dry deposition fluxes (0 = No)	0
IWPRT	Print wet deposition fluxes (0 = No)	0
ICFRQ	Concentration print interval (1 = hourly)	1
IDFRQ	Dry deposition flux print interval (1 = hourly)	1
IWFRQ	West deposition flux print interval (1 = hourly)	1
IPRTU	Print output units (1 = g/m**3; g/m**2/s)	1
IMESG	Status messages to screen? (1 = Yes)	1
Output Species	Where to output various species	**User Defined**
LDEBUG	Turn on debug tracking? (F = No)	F
Dry Gas Dep	Chemical parameters of gaseous deposition species	**User Defined**
Dry Part. Dep	Chemical parameters of particulate deposition species	**User Defined**
RCUTR	Reference cuticle resistance (s/cm)	30.
RGR	Reference ground resistance (s/cm)	10.
REACTR	Reference reactivity	8
NINT	Number of particle-size intervals	9
IVEG	Vegetative state (1 = active and unstressed)	1
Wet Dep	Wet deposition parameters	**User Defined**
MOZ	Ozone background? (1 = read from ozone.dat)	1
BCKO3	Ozone default (ppb) (Use only for missing data)	**80**
BCKNH3	Ammonia background (ppb)	**10**
RNITE1	Nighttime SO2 loss rate (%/hr)	0.2
RNITE2	Nighttime NOx loss rate (%/hr)	2
RNITE3	Nighttime HNO3 loss rate (%/hr)	2

Variable	Description	Value
SYTDEP	Horizontal size (m) to switch to time dependence	550.
MHFTSE	Use Heffter for vertical dispersion? (0 = No)	0
JSUP	PG Stability class above mixed layer	5
CONK1	Stable dispersion constant (Eq 2.7-3)	0.01
CONK2	Neutral dispersion constant (Eq 2.7-4)	0.1
TBD	Transition for downwash algorithms (0.5 = ISC)	0.5
IURB1	Beginning urban landuse type	10
IURB2	Ending urban landuse type	19
Use Following Only For Single-Point Meteorological Input (CALPUFF Screen)		
ILANDUIN	Land use type (20 = Unirrigated agricultural land)	20
ZOIN	Roughness length (m)	0.25
XLAIIN	Leaf area index	3
ELEVIN	Met. Station elevation (m above MSL)	0
XLATIN	Met. Station North latitude (degrees)	**User Defined**
XLONIN	Met. Station West longitude (degrees)	**User Defined**
ANEMHT	Anemometer height of ISC meteorological data (m)	10.0
ISIGMAV	Lateral turbulence (Not used with ISC meteorology)	1
IMIXCTDM	Mixing heights (Not used with ISC meteorology)	0
End of Single Point Meteorology Input Variables		
XMXLEN	Maximum slug length in units of DGRIDKM	1
XSAMLEN	Maximum puff travel distance per sampling step (units of DGRIDKM)	1

Variable	Description	Value
MXNEW	Maximum number of puffs per hour	99
MXSAM	Maximum sampling steps per hour	99
SL2PF	Maximum Sy/puff length	10
PLX0	Wind speed power-law exponents	0.07,0.07,0.10,0.15,0.35,0.55
WSCAT	Upper bounds 1st 5 wind speed classes (m/s)	1.54,3.09,5.14,8.23.10.8
PGGO	Potential temperature gradients PG E and F (deg/km)	0.020, 0.035
SYMIN	Minimum lateral dispersion of new puff (m)	1.0
SZMIN	Minimum vertical dispersion of new puff (m)	1.0
SVMIN	Array of minimum lateral turbulence (m/s)	6*0.50
SWMIN	Array of minimum vertical turbulence (m/s)	0.20, 0.12, 0.08, 0.06, 0.03, 0.016
CDIV	Divergence criterion for dw/dz (1/s)	0.01
WSCALM	Minimum non-calm wind speed (m/s)	0.5
XMAXZI	Maximum mixing height (m)	3000
XMINZI	Minimum mixing height (m)	50
PPC	Plume path coefficients (only if MCTADJ = 3)	0.5,0.5,0.5,0.5,0.35,0.35
NSPLIT	Number of puffs when puffs split	3
IRESPLIT	Hours when puff are eligible to split	**User Defined**
ZISPLIT	Previous hour’s mixing height (minimum), (m)	100
ROLDMAX	Previous Max mixing height/current mixing height ratio, must be less then this value to allow puff split	0.25

Variable	Description	Value
EPSSLUG	Convergence criterion for slug sampling integration	1.0E-04
PESAREA	Convergence criterion for area source integration	1.0E-06
NPT1	Number of point sources	User Defined
IPTU	Units of emission rates (1 = g/s)	1
NSPT1	Number of point source-species combinations	0
NPT2	Number of point sources with fully variable emission rates	0
Point Sources	Point sources characteristics	User Defined
Area Sources	Area sources characteristics	User Defined
Line Sources	Buoyant lines source characteristics	User Defined
Volume Sources	Volume sources characteristics	User Defined
NREC	Number of user defined receptors	User Defined
Receptor Data	Location and elevation (MSL) of receptors	User Defined

APPENDIX C
COMPACT DISK DATA RESOURCES

Solar and Meteorological Surface Observation Network (SAMSON), 1961 - 1990
Version 1.0, September 1993

Available from U.S. Department of Commerce, National Climatic Data Center, Federal Building, 37 Battery Park Ave., Asheville, NC 28801

Radiosonde Data of North America, 1946 - 1992
Version 1.0, August 1993

Available from U.S. Department of Commerce, National Climatic Data Center, Federal Building, 37 Battery Park Ave., Asheville, NC 28801

CALMET, CALPUFF, and CALPOST Modeling System
Version 1.0

Available from U.S. Department of Commerce, National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161. NTIS PB 96-502 083.

Hourly United States Weather Observations (HUSWO) 1990-1995

Available from U.S. Department of Commerce, National Climatic Data Center, Federal Building, 37 Battery Park Ave., Asheville, NC 28801

MM4 - 1990 Meteorological Data, Volumes 1-12

Available from U.S. Department of Commerce, National Climatic Data Center, Federal Building, 37 Battery Park Ave., Asheville, NC 28801

NCDC Precipitation data CD's

Available from U.S. Department of Commerce, National Climatic Data Center, Federal Building, 37 Battery Park Ave., Asheville, NC 28801

APPENDIX D
SIXTH MODELING CONFERENCE

Section 320 of the 1990 CAA amendments requires the EPA to conduct public conferences on air quality modeling at least every three years. These conferences are to give special attention to appropriate modeling necessary for addressing prevention of significant deterioration of air quality. The sixth of these modeling conferences was held August 9-10, 1995 in Washington, D.C. One of the main topics discussed at the sixth conference was a review of the status of work by IWAQM in the development of a Phase 2 recommendation. At the conference comments were presented by several attendees regarding their experiences in applying the Phase 1 interim recommendations, and thoughts and recommendations were presented on future needs. The presentation results, comments received and conclusions reached at the Sixth Modeling Conference are fundamental to the development of the Phase 2 recommendations, and will be discussed in the following sections.

D.1 Presentation Summary

The IWAQM presentation at the Sixth Modeling Conference began with a review of the work plan (U.S. EPA, 1992a) and the Phase 1 interim recommendations (U.S. EPA, 1993), which have briefly been discussed above. The presentation then provided a summary of work accomplishments in five areas: 1) results from a case study conducted using the Phase 1 interim recommendations; 2) adaptations made to a Lagrangian puff modeling system called CALPUFF; 3) MESOPUFF II and CALPUFF simulation results for three of the 1983 Cross APpalachian Tracer EXperiment (CAPTEX) tracer releases; 4) conclusions reached regarding use of sophisticated mesoscale meteorological analyses; 5) a proposed process for modeling specific Class I areas. In the following five subsections, brief summaries are presented for each of the topics listed. More extensive summaries are presented in Section 4.

D.1.1 MESOPUFF II Implementation Assessment

The objective was to learn by experience where the difficulties are in the process of applying the MESOPUFF II air quality modeling system following IWAQM Phase 1 interim recommendations (U.S. EPA, 1993) and when possible, to provide a means for resolving these difficulties. It was not an objective to provide a meaningful assessment of PSD, NAAQS or AQRV impacts for the Class I areas considered in the study. As part of this study the following tasks were carried out:

- The MESOPUFF II model and associated processors were tested using the example problem intended for Support Center for Regulatory Air Models bulletin board (SCRAM BBS) distribution. The SCRAM BBS example problem computer files were evaluated and some suggested improvements were implemented.

- A five-year meteorological data set suitable for input to the MESOPUFF II model was developed for a multi-state area surrounding Shenandoah National Park (SNP), including the James River Face (JRF) wilderness area. Model simulations were performed using three years of the developed five-year meteorological data set to demonstrate the assessment of visibility, acidic deposition, and PSD increments for a set of real sources in the states surrounding Shenandoah National Park.

- Model simulations were performed to test the sensitivity of concentrations to the distance between sources and receptors using a set of "pseudo" sources placed in successive rings around Shenandoah National Park.

Several conclusions were reached as a result of the demonstration assessment. First, tailoring a puff simulation analysis to assess PSD and AQRV impacts at SNP and JRF was a difficult task. A primary goal is to develop a reasonably good characterization of the spatially-varying, time-varying three dimensional wind field. This goal alone requires an air pollution modeler with strong dispersion meteorology experience, having expert judgement and finesse. The differing goals between PSD permitting and AQRV assessment required frequent consultation with FLMs. Since the modeling necessarily required case-specific judgement decisions, strong collaboration and review was required by the various regulatory reviewing authorities. All these considerations have caused IWAQM to believe in and recommend a Regional Approach, as discussed in Section 4.5.

Even with anticipated improvements in the software, it is likely that the analyses will require programming special routines to convert data into appropriate formats, or to assist in the analysis and summarization of the data. Also even though the modeling software can be executed on personal computers, it is likely that a workstation would prove more convenient and useful. Thus it is concluded that mesoscale analyses using Lagrangian puff dispersion models must be viewed as more involved and difficult than using conventional plume dispersion models. This is especially true in consideration that most plume dispersion modeling assessments use a single-station's hourly meteorological observation, whereas puff dispersion modeling is founded on using a three-dimensional wind field, that is consistent with the terrain and land-use.

The PSD and AQRV impacts developed in the demonstration assessment from the ten aggregated sources exhibited strong year-to-year variations. Furthermore, some of the impacts were close to the PSD increments. These results suggest that at least three years of modeling is needed in order to assess the likely maximum impacts. Part of the reason for recommending a Regional Approach is to address concerns that more attention needs to be given to comparing PSD and AQRV impacts generated by all the sources as a the cumulative impact assessment.

The ring source analysis illustrates some of the effects of source-receptor distance on air quality and deposition impacts. For the primary species, SO_2 and NO_x,

peak impacts declined rapidly with distance. MESOPUFF II results suggest that sources of the size used for this analysis (183 g/s SO_2), located 50 km from SNP, are capable of producing 3-hour SO_2 impacts close to the allowable PSD Class I increment. For the secondary species, $SO_4^=$ and NO_3^-, impacts did not show a decreasing trend for sources between 50 km and 200 km from SNP. Although modeled PM_{10} concentrations were well below allowable PSD Class I increments for all rings, the lack of a clear trend suggests that sources beyond 200 km may need to be considered in some cases in order to assess the impact upon PM_{10} and related parameters, such as visibility.

D.1.2 Revisions to CALMET and CALPUFF

In the course of completing the Phase 1 recommendations, IWAQM became aware of the CALMET/CALPUFF modeling system (Scire et al., 1990ab), which was actively under development. Building from lessons learned from the MESOPAC/MESOPUFF II modeling system, IWAQM felt further enhancements were needed in two areas. With a view towards allowing one model to be used for all sources (which might include source-receptor distances of less than 50 km), the first area for enhancement was to include within CALPUFF dispersion additional algorithms, so that CALPUFF simulation results would be consistent with the Industrial Source Complex (ISC) model and the Complex Terrain Dispersion Model (CTDMPLUS) (Perry et al., 1989) modeling results for steady-state meteorological conditions. Both ISC and CTDMPLUS are recommended in the *Guideline* for use for source-receptor distances of less than 50 km. The second area for enhancement to the CALMET/CALPUFF modeling system was to include provisions within CALMET to allow use of mesoscale meteorological modeling results created using data assimilation techniques, for example Stauffer and Seaman (1989) and Stauffer et al. (1990). The characterization of the time-varying three-dimensional wind field is one of the most challenging issues for long-range transport.

<u>Consistency with local-scale plume dispersion models.</u>

At the Sixth Modeling Conference, IWAQM reported on the inclusion within CALPUFF of dispersion algorithms to provide results consistent with ISC and CTDMPLUS. At the time of the conference, there were only preliminary sensitivity testing results to show that the modifications to CALPUFF would be successful in mimicking ISC. There were no comparison results available showing consistency between CALPUFF and CTDMPLUS. It was recognized and mentioned by IWAQM at the Sixth Modeling Conference that more testing was needed to test whether the code modifications implemented in CALPUFF would replicate dispersion results as would be simulated by ISC and CTDMPLUS.

Enhancement of CALMET for mesoscale applications.

The wind field module in CALMET is based on the Diagnostic Wind Model (DWM). In anticipation of using CALMET and CALPUFF for long-range transport distances, a series of modifications were made (U.S. EPA, 1995b). The DWM in CALMET uses a two step procedure in developing the final wind fields. An initial guess field is developed based on a domain-average wind profile, and this domain-average profile of winds is adjusted for terrain effects and divergence minimization to produce a “Step 1" wind field. The second step in the processing of the wind field is the introduction of the observational data into the terrain adjusted Step 1 wind field.

The adaptations needed to allow use of meteorological wind fields as analyzed by sophisticated mesoscale meteorological models (hereafter referred to as *FDDA-MM data*) involved more than simply providing a new data input option. (For further discussion of Four Dimensional Data Assimilation (FDDA) and how such data sets are constructed, see Section 4.4.) IWAQM was confident that since the surface and upper-air observations are included as part of the data assimilation process, the mesoscale meteorological analyses from such analyses could be treated as data. But IWAQM was aware that inherently such data are representative of a certain scale, as defined by the physics included in the numerical equations and by the grid scale of the results. Therefore, CALMET was modified to allow introduction of the *FDDA-MM data* 1) as input in the creation of the CALMET Step 1 wind fields; 2) as the CALMET Step 1 wind fields; or 3) as input in the creation of the CALMET Step 2 wind fields.

At the Sixth Conference, results from a series of sensitivity analyses were reported investigating how to combine the *FDDA-MM* data with observations, and investigating the impact of *FDDA-MM* data on simulated trajectory results. The sensitivity analyses were conducted for two episodes in eastern United States, one summer episode (August 1-6, 1988) and one winter episode (December 3-10, 1988). The summer episode was characterized by light wind, stagnant conditions. The winter episode was characterized as an active period that included the passage of a front and low-pressure system through the domain. Penn State Mesoscale Meteorological (version 4) modeling results (MM4) were available employing four dimensional data assimilation (Stauffer and Seaman, 1989) for both episodes and for three different grid resolutions, 18-, 54- and 80-km. The CALMET model was run using hourly weather observations from 119 surface stations for both episodes, and used twice-daily observations from 25 upper-air stations for the summer episode and 23 upper-air stations for the winter episode. In general, the introduction of the 80-km MM4 winds improved the ability of CALMET to reproduce the reference 54- and 18-km MM4 wind fields. Slightly better agreement was achieved when the 80-km MM4 winds were brought in after the diagnostic terrain adjustment procedures (i.e., as the Step 1 wind fields or as “observations”). This was conjectured to occur due to the fact that 1) the 80-km MM4 are already close to the 54- and 18-km MM4 results, and 2) the CALMET diagnostic adjustments may duplicate terrain effects that were already accounted for in the development of the 80-km MM4 winds. From the numerical sensitivity tests,

IWAQM concluded that using *FDDA-MM* wind fields adds a noticeable and significant improvement in the characterization of trajectories of the dispersing material within the atmosphere.

D.1.3 Trajectory Comparisons

As discussed in the previous section, modifications were made to CALMET in anticipation of using CALMET and CALPUFF for long-range transport distances (U.S. EPA, 1995b). It was anticipated that use of *FDDA-MM* winds would improve CALPUFF's characterization of trajectories of dispersing pollutants. To further investigate this, two trajectory studies were conducted: 1) comparisons with simulated trajectories, and 2) comparisons with trajectories derived from surface tracer monitoring.

<u>CALMET trajectory comparisons.</u>

Trajectories were computed from four release locations at three levels (10 m, 200 m, and 400 m) for each of the wind fields discussed in Section 4.1.2 for the summer episode (U.S. EPA, 1995b). Trajectories were generated at each location every 4, 6 and 12 hours from the beginning of the simulation, for up to 24 hours before the end of the simulation. A statistical analysis was conducted on the trajectories to assess the effect of the different wind fields.

Trajectory statistics were computed from each release time and for all three levels. In general, the introduction of the 80 km MM4 winds into CALMET to develop either 54 km or 18 km gridded wind fields significantly improved the comparisons with the trajectories developed from the 54 km and 18 km MM4 wind fields directly, versus using only the routine hourly weather observations and twice-daily upper air observations as input to CALMET.

<u>CAPTEX comparisons</u>

One of the primary objectives of this study was to assess whether use of mesoscale dynamic wind fields developed using *FDDA-MM* data exhibited improved spatial and temporal resolution versus typical mesoscale wind fields determined diagnostically from the available hourly surface and twice-daily upper air observations, would improve the quality of the characterization of the transport and dispersion. Results were presented for CAPTEX releases 3, 5 and 7 (Irwin et al., 1996). The Cross-APpalachian Tracer EXperiment (CAPTEX) is a unique series of tracer releases which, besides testing a particular tracer technology, was conducted for the purpose of providing insight into the mechanisms involved in long-range transport and dispersion (Ferber et al., 1986). A three-hour ground-level release of perfluoromonomethyl-cyclohexan (C_7H_{14}, PMCH) was made five times near Dayton, Ohio and twice from near Sudbury, Ontario when winds were expected to transport the tracer over the ground-level sampling network. Samplers were operated at 86 sites in Ohio, Pennsylvania,

New Jersey, New York, New England and southern Canada at distances from 300 to 1100 km from the release site. Air concentrations were collected for 3 and 6 hour durations for several days following each release.

Meteorological data available for use in developing the CAPTEX wind fields consisted of 122 National Weather Service (NWS) surface locations reporting hourly and 13 upper-air locations reporting twice-daily (0000 GMT and 1200 GMT) throughout the region. Furthermore, mesoscale wind fields developed using Version 8 of the Penn State/NCAR Mesoscale Model - Generation 4 (MM4) were available on an 80-km grid. Three wind field models were used to obtain a gridded field of meteorological data with a horizontal resolution of 18-km: MESOPAC II, CALMET, and CALMET using the mesoscale wind fields as STEP-1 inputs. The latter modeled wind fields were developed using FDDA and are referred to as CALMET/MM4.

The comparison results presented were conducted with simplified puff dispersion model assumptions, hence the model-to-model differences were minimized. It was concluded there was a noticeable improvement in the simulation of the puff centroid trajectories, when the wind fields were developed using *FDDA-MM* data, versus developing the wind fields diagnostically from the available hourly surface and twice-daily upper air observations. The analysis of the concentration maxima and lateral dispersion values suggest that the simulation assumptions employed in these results consistently underestimate the horizontal extent of the tracer puff as it is transported downwind. The centroid maximum surface concentration was found to be correspondingly overestimated and relatively insensitive to the mesoscale wind characterization. In these simulations, no provisions were made to address delayed shear enhancement of the dispersion as described by Moran and Pielke (1994) and Shi et al. (1990). Inclusion of some sort of puff splitting is obviously warranted, but the computational demands are not trivial if one is attempting to develop an operational model for routine use. Furthermore, in those cases where the puff model dynamics have been enhanced, for example Draxler (1987) and Davis et al. (1986), there was a tendency to underestimate the surface maximum concentrations.

D.1.4 Constructing *FDDA-MM* Data Sets Assessment

To foster use of mesoscale meteorological (MM) data processed using Four Dimensional Data Assimilation (FDDA) in routine air pollution modeling assessments and to learn what problems might be associated with such a project, a one-year meteorological data set for 1990 was fabricated that spans the contiguous United States, southern Canada and northern Mexico. The 1990 data set (NCDC, 1995) was somewhat dated when it was discussed at the Sixth Modeling Conference. Yet it still represents a significant advancement to meteorological characterizations employed in many current routine air pollution assessments. These data were made available to allow investigators to have access to this type of data that they might otherwise not have access to (NCDC, 1995), with the hope that this would stimulate investigations, exploring the strengths and weaknesses of these data in a variety of ways.

The 1990 data set consist of hourly profiles of wind, temperature and moisture at 23 levels in the atmosphere on an 80-km grid spacing. The Penn State mesoscale meteorological model (MM4) with FDDA was used in developing these data. The horizontal grid spacing of the MM4 simulation was 80 km in both dimensions, with a grid array size of 85 by 56 centered on 90 W longitude and 40 N latitude to cover most of the North American continent and adjacent oceanic areas (Bullock, 1993). The domain of the model's vertical coordinate system extended from the earth's surface to the 100 millibar pressure level (approximately 15 km above sea level). It's 15-level structure provides height-resolved information similar to that routinely obtained by the National Weather Service at 12-hour intervals from approximately 80 rawinsonde balloon sounding locations across North America. However, the data set obtained from the MM4 simulation provides synthetic soundings at 1-hour intervals for 4080 model grid-point locations, or about 600 times more information than is available from routine observational networks. The 1990 data set is comprized of over 20 billion bytes of information.

One of the lessons learned in developing the 1990 data set was that the science of mesoscale analysis using data assimilation is rapidly developing. Major advancements have been occurring every several months during the period from 1995 through 1997. There are various research groups with active development programs investigating mesoscale meteorological modeling employing data assimilation, e.g. Pielke et al., (1997). This suggests that developing and maintaining a multi-year data set would likely involve a substantial committment in resources. An alternative to commissioning special one-year runs would be to use results from an existing operational ongoing activity (Pielke and Uliasz, 1997). One such activity is a product that currently is under development and refinement by the NOAA Environmental Modeling Center Mesoscale Modeling Branch. They are employing a mesoscale numerical weather prediction model, known as the NCEP ETA Model, with data assimilation. This mesoscale meteorological model produces analyses of the vertical profiles of wind, temperature, pressure and moisture on a 48 km grid resolution that covers a very large domain (e.g., as far west as the Hawaiian Islands, all of the contiguous United States, as far north as all of Alaska). The current operational output provides information for 38 layers in the vertical. The model employs a surface moisture balance model (Chen et al., 1997), and hence is capable of reporting the surface heat and moisture fluxes, soil moisture, and precipitation (amounts for both wet, frozen and snow).

The Environmental Modeling Center (EMC) Home Page is: http://nic.fb4.noaa. gov:8000/. The ETA model outputs are produced by the Mesoscale Modeling Branch (MMB). The Mesoscale Modeling Branch Home Page is: http://nic.fb4.noaa.gov:8000 /research/mesoscale2.html.

A major obstacle is access to these data. The 1990 MM4 data set in a compressed format (providing only profiles of wind, temperature and moisture) requires 12 Compact Diskettes. An operational means for gaining easy access to

comprehensive mesoscale meteorological data sets, as alluded to here, has yet to be developed. But IWAQM believes that the future of air quality modeling requires a solution being found to gain routine inexpensive access to such data. And IWAQM believes that it is only a matter of time (perhaps less than three years) that such a solution could be found.

D.1.5 Regional Approach

The effective treatment of mesoscale transport of pollutants requires treatment of the time and space variations of the three-dimensional meteorological conditions. This in turn involves consideration of the variations in terrain heights and land-use, and their consequent effects on the dispersive characteristics of the atmosphere. A major issue in assessing mesoscale impacts to specific Class I areas from specific sources is giving due consideration to the proper characterization of the transport (trajectory) of the pollutants. As alluded to in the discussion of Section 4.1, where MESOPUFF II was used to assess impacts on the Shenandoah National Park, and in Section 4.3, where the characterization of the transport trajectories was investigated, this is not a process that lends itself to a cookbook approach. Tailoring the wind field analysis will require technical judgement and discretion, and IWAQM has come to the opinion that these case-specific decisions are best achieved using a team of experts and development of a consensus.

The discretion and case-specific decision making does not apply soley to the implementation of the dispersion modeling. Not all wilderness areas have the same flora and fauna. The AQRVs of interest will be specific to each wilderness area. Developing an inventory with agreed upon emission rates is not trivial. The inventory could differ depending on whether the analysis is addressing NAAQS assessments (which typically address maximum allowable emission rates from PSD sources) versus AQRV assessments (which typically address actual current emission rates from all sources).

Therefore at the Sixth Modeling Conference, IWAQM suggested that Class I air quality modeling assessments be designed for each Class I area (or cluster of Class I areas), rather than for each permit as is the case for the Class II program. The cornerstone of this approach is an up-front comprehensive increment and AQRV analysis of the area. This "initialization" study would be accomplished outside the context of a permit application, and could involve technical experts from private and public groups. Perhaps most importantly, it provides future applicants with up-front information needed for planning and assurance of what is expected for the given situation.

D.1.6 Sixth Modeling Conference IWAQM Recommendations

At the Sixth Modeling Conference, IWAQM recommended that the CALPUFF modeling system (Scire et al., 1995a,b) replace the MESOPUFF II modeling system.

Based on sensitivity studies and the CAPTEX comparisons of results obtained by the two modeling systems, IWAQM had concluded that the CALPUFF modeling system was at least as good as the MESOPUFF II modeling system, and offered several improvements. For one, the CALPUFF modeling system code was better documented and was believed to be better engineered. Graphical User Interface (GUI) applications were under development to assist and make easier the use of the CALPUFF modeling system. CALMET had been enhanced to allow use of *FDDA-MM* mesoscale meteorology. CALPUFF had been enhanced to allow better correspondence with local-scale (less than 50 km transport) models recommended for use in the *Guideline*. These latter enhancements provided the basis for allowing one model to be used for all sources in a mesoscale assessment, even though for some of the sources the transport might be less than 50 km. At the time of the Sixth Modeling Conference, the CALPUFF modeling system was not available from the EPA Support Center for Regulatory Models (SCRAM) electronic Bulletin Board Service (BBS), but it was anticipated that it would soon be available in an area designated "Topics for Review and Comment."

Even though such data were not available, nor was it likely that IWAQM would be able to develop such data, IWAQM recommended that use of *FDDA-MM* mesoscale meteorological data be approved in regulatory assessments. The comparisons between alternative methods for developing CALMET wind fields, and the comparisons of the resulting trajectories, suggested to IWAQM that the added skill in the assessment was dramatic and desirable. There were (and still remain) serious logistical issues to development and use of such data. But in each case where such data have been used, the characterization of the trajectories has improved.

Finally, given the myriad of decisions needing to be made in most mesoscale assessments of transport and dispersion impacting Class I areas, IWAQM recommended that a Regional Approach be used to resolve the various decisions. This involves assembling a committee of the various public and private stakeholders, and gaining consensus that the committee will be proactive in developing a plan to chart a course through the specific decisions needing to be made for the Class I area they are concerned with, and following the developed plan. For those seeking permits, being able to go to such a committee for information is of great benefit. It insures that all applicants are treated equitably, and it allows packaging of the results from each applicant in a manner that supports cumulative impact tracking and assessment. If the committee sponsors development of meteorological data sets, these can be made available to the applicants to save costs and time.

D.2 Summary Of Sixth Modeling Conference Comments

One commenter pointed out the practical deficiencies with straight line plume transport models and strongly urged the development and adoption of a trajectory model. Another commenter pointed out the technical superiority of CALPUFF over the best Gaussian models EPA supports. The commenter urged that the advantages and applicability of CALPUFF be discussed among state and regional modeling contacts,

that evaluation and comparison data be amassed, and that early consideration be given to case-by-case regulatory applications of CALPUFF.

Another commenter noted that "[The IWAQM] apparently did not address the question of whether or not [an air quality analysis beyond 50 km] can be done with the hope of reaching any reasonable answer." The commenter argued that there is no accurate way to do this. The commenter also noted that IWAQM did not address the accuracy of the Phase I screening analysis (Level I) or refined analysis (Level II). Also, the results were not qualified (i.e., level of conservatism was not stipulated). It was recommended that IWAQM qualify the accuracy of the results. For Level I analyses, it was recommended that IWAQM remove the stagnation and recirculation wording and that IWAQM specify with "reasonable particularity" the *Guideline* models to be used, that some reasonable yet conservative and consistent conversion rates for both visibility and deposition be assumed, and that the Level I analysis be a true screen. For Level II analyses, the commenter recommended that, if a preapproved protocol is required, the regulatory and FLM agencies must agree to abide by the results and that on-site meteorological data not be required. The commenter believes that in some cases the regulatory need to analyze long-range impacts is beyond the state-of-the-practice, and that IWAQM failed to portray how conservative such calculations really may be. Several figures were included to illustrate the commenter's contention that CALPUFF would have severe difficulty simulating accurate concentrations on the back side of terrain along certain transects near the Rockies.

Aside from the more specific comments mentioned above, the commenters all seemed in agreement that the Regional Approach outlined by IWAQM was desirous. There seemed general agreement that the Level I screen suggested in the Phase I interim recommendations was not working well and needed to be improved. There was also general agreement that the CAPTEX comparisons were for transport distances of 300 to 1000 km, well beyond the anticipated range of PSD Class I impact assessments. Therefore, more comparisons with tracer data studies for transport distances of order 50 to 200 km were needed. Finally, although only mentioned by the last commenter, there was a sense that mesoscale transport assessments may be very difficult analyses, involving discretion and expert judgment. In some instances, the modeling results would be so uncertain as to preclude them of being any use.

D.3 Response to Sixth Modeling Conference Comments

The comments received at the Sixth Modeling Conference can be summarized into several general areas: 1) there seemed to be agreement that the Regional Approach outlined by IWAQM was desirous; 2) there was general agreement that as the CAPTEX comparisons were for transport distances of 300 to 1000 km, well beyond the anticipated range of PSD Class I impact assessments, that more comparisons with tracer data studies for transport distances of order 50 to 200 km were needed; 3) there was general agreement that the Level I screen suggested in the Phase I interim recommendations was not working well and needed to be improved; 4) there was

agreement that comparisons were needed to assess whether CALPUFF can provide results similar to ISC and CTDMPLUS for steady-state meteorological conditions; and 5) finally there was a sense that mesoscale transport assessments may be difficult analyses (perhaps impossible in some cases), requiring discretion and expert judgment.

Regional Approach

It has been IWAQM's experience that most long-range transport dispersion assessments involve expert judgement and finesse in order to provide a reasonable characterization of the transport and dispersion with the information and resources available. The process has yet to be successfully accomplished using "cookbook" procedures. To further complicate matters, the AQRV's of interest are typically specific to the Class I area and climate, and thus the modeling endpoints need to be customized to address the site-specific issues of concern. It is therefore understandable that most people concur with the recommendation by IWAQM to employ committees of technical experts, whenever possible, to sort through the various decisions and tradeoffs. It also understandable that most people would endorse having a panel of experts dedicated to a particular Class I area (or areas) that could provide some consistency in the modeling assessments and assist in addressing site-specific questions as they arise. But just as some of the options in an air quality modeling system can not be automatically prescribed, the same can be said for use of technical committees. Hence, while IWAQM endorses use of such committees, IWAQM does not recommend Federal agencies mandate or require their use.

Model evaluations for the 50 to 200 km range

There are very few tracer dispersion field studies with sufficient sampling to depict with some certainty the relative location of the receptors to the puff of dispersing tracer as it was transported downwind. In fact, the number of studies is so small that comparison results that can be developed only provide anecdotal evidence regarding model performance. In response to the suggestion that comparison results be developed for transport of order 50 to 200 km, IWAQM commissioned studies for four tracer dispersion experiments. A summary of the findings for each of the four tracer studies is provided in Section 4.6. Three of these field studies involved 3 to 4 hour releases that were then sampled along arcs of receptors downwind. In some cases, shorter-term concentration values were available, such that the transport of the puff past an arc could be seen. Differences on the order of 10 to 20 degrees were seen between the simulated and observed center of mass of the puff as it passed the receptor arc. Most of the simulated centerline concentration maxima along each arc were within a factor of two of those observed. In those instances when large over- or underpredictions occurred, there was insufficient information available to ascertain the physical processes that resulted in the observed concentration values. Without a better understanding of the physical dispersion processes affecting these instances, no simulation has (or likely will) show skill.

It was concluded from these admittedly anecdotal case studies, that CALPUFF is performing in a reasonable manner, and has no apparent bias towards over- or under-prediction. This is in contrast to the CALPUFF comparison results with the CAPTEX tracer field data, where CALPUFF consistently underestimated the 'footprint' of the puff in contact with the surface, and correspondingly overestimated the puff concentration maxima by a factor of 2 or more. This suggests CALPUFF (as configured for the CAPTEX comparisons) was poorly characterizing dispersion processes (such as delayed shear enhancement) which become important for transport distances of order 300 km or more. It is concluded that CALPUFF will need to be further developed before it can more realistically characterize transport and dispersion for more than one diurnal cycle.

The IWAQM concludes that CALPUFF can be recommended as providing unbiased estimates of concentration impacts for transport distances of order 200 km or less, and for transport times of order 12 hours or less. For larger transport times and distances, our experience thus far is that CALPUFF tends to underestimate the horizontal extent of the dispersion and hence tends to overestimate the surface-level concentration maxima. This does not preclude the use of CALPUFF for transport beyond 300 km, but it does suggest that results in such instances be used cautiously and with some understanding.

Comparisons with ISC and CTDMPLUS

At the time of the Sixth Modeling Conference, the algorithms installed in CALPUFF to allow it to mimic ISC and CTDMPLUS had not been thoroughly tested. In response to the need for further comparisons, a thorough investigation and comparison with ISC was completed. A similar investigation is needed but has yet to be accomplished with CTDMPLUS. A summary of the comparison results with ISC is presented in Section 4.7.

As expected, when the meteorological conditions were steady-state (fixed wind direction, wind speed, mixing height, and stability), there were only minor differences seen between ISC and CALPUFF. For all of the point source and volume source comparisons, the differences seen between ISC and CALPUFF were less than one percent. The largest differences were seen for receptors within and near the downwind edge of a simulated area source. For the area source comparisons, the differences on average were less than four percent, but individual cases were seen with larger differences. These larger differences seen with the area source are traceable to the difficulty of efficiently replicating the plume model's characterization of an area source. The IWAQM concluded that, for all practical purposes, although improvements might be made, the algorithms within CALPUFF are capable of replicating the results of ISC for steady-state meteorological conditions.

When the meteorology was allowed to vary from one hour to the next, but not in space, large differences were seen in the simulated highest and second-highest

concentrations for all averaging times examined (1-hour, 3-hour, 24-hour, and annual) and for all distances downwind out to 300 km. In general, CALPUFF was seen to provide higher surface-level concentration impacts than ISC in those special situations where the preceding hours had several hours of calm winds, or involved a dramatic wind reversal and caused previously released material to be simulated to combine with newly released material. Given that ISC ignores impacts during calm wind conditions, and can not characterize the 'causality' resulting from a buildup of material during an extended period of calm winds or a reversal in the transport winds, such differences were expected.

The IWAQM concludes that CALPUFF does reproduce, for all practical purposes, the results that would be obtained using the ISC plume dispersion model, when the meteorological conditions are steady-state. For situations involving complex winds conditions (frequent periods of extended calms, routine and periodic wind reversals, complex topographical wind effects and channeling, etc.), where a local-scale plume dispersion model (such as ISC) is the recommended modeling approach, IWAQM recommends acceptance on a case-by-case basis the results obtained using the CALPUFF modeling system. In these situations, the three-dimensional time-varying wind field and the 'causality' from one hour to the next are most important in deriving an assessment of the impacts associated with the transport and dispersion of pollutants.

In conducting the comparisons of CALPUFF with ISC, minor inconsistencies were found and corrections were made to the CALPUFF algorithms, so that the CALPUFF results would replicate (to the extent a puff model can) the results that would be obtained by a plume model for steady-state meteorological conditions. A similar intensive inspection of the CTDMPLUS algorithms within CALPUFF has yet to be accomplished. Once such an investigation has been completed (assuming that CALPUFF can be made to provide results acceptably similar to those obtained with CTDMPLUS for steady-state meteorological conditions), then IWAQM would endorse use of results from the CALPUFF modeling system on a case-by-case basis, in lieu of those obtained from the CTDMPLUS model, for complex wind situations.

Develop a better screen technique

At the Sixth Modeling Conference, the 'Level I' technique suggested in IWAQM Phase I interim recommendations (EPA, 1993), of using as a screening model results for the ISC dispersion model, was generally considered inadequate. The Level I screening estimates of the AQRV impacts were considered so conservative that only sources with very small emissions were 'screened' from further consideration. In response to these comments, a study was conducted in an attempt to construct a more meaningful and useful screening technique, a summary of which is presented in Section 4.8.

By far the most demanding task to successfully accomplish is to develop a valid time and space varying characterization of the meteorological conditions for use by the

CALPUFF puff dispersion model. Thus IWAQM concluded that if a simplification could be made in specifying the meteorological conditions, perhaps CALPUFF could be used to develop the screening estimates of pollutant impacts. This would allow the chemistry and fate to be appropriately characterized, and at least some of the 'causality' effects would be captured. It was with this background and understanding that IWAQM investigated developing a screening estimate using CALPUFF with a highly simplified characterization of the meteorological conditions.

In the course of the development of the CALPUFF modeling system, options were implemented that allow the meteorological conditions to be specified using either the meteorological input required for the ISC model, or the meteorological input required for the CTDMPLUS model. These optional formats for specifying the meteorology to CALPUFF were implemented initially to facilitate testing of ISC and CTDMPLUS algorithms in CALPUFF. The IWAQM decided to pursue development of a screening estimate that could be made using the meteorological input for the ISC model, as input to CALPUFF.

One of the consequences of simplifying the meteorological input to that of the ISC model, is all terrain effects (channeling, slope flows, etc.) are lost. The consequence of these effects can become important in assessing pollutant impacts for specific source-receptor combinations. To counter for the loss of properly characterizing the spatial variations in the meteorological conditions, it was decided that rings of receptors would be used that completely surround the source under analysis. The rings would be placed to pass through the Class I area(s) of concern, and would be spaced to provide suitable coverage, using expert judgement and in agreement with applicable reviewing authorities. The maximum pollutant impacts (increment, AQRV, etc.) found anywhere on any of the rings of receptors would be used as the screening impact estimate of the pollutant impact. Selecting only receptors within the particular Class I area(s) is not appropriate, as the screening analysis as designed does not address the spatial variations in the meteorological conditions.

As summarized in Section 4.7, use of ISC meteorological input does not guarantee that the maximum SO_2 concentration found on a ring of receptors is consistently estimated to be larger than what would be found if a complete three-dimensional time-varying wind field and meteorological conditions were used, all other factors being equal. In the sensitivity tests conducted, the longer the averaging time of the SO_2 concentration, the more likely the maximum for a ring of receptors will be similar, whether ISC or CALMET meteorology input is used. The CALPUFF screening estimates of sulfate concentrations and deposition were consistently much less than would be estimated using IWAQM Phase 1 Level 1 ISC procedures. The CALPUFF screening estimates of sulfate concentrations and deposition were sometimes higher and sometimes lower than that seen using full CALMET input to CALPUFF.

It is concluded by IWAQM that using five years of ISC meteorology as input to CALPUFF, and selecting the maximum concentration from rings of receptors that

completely surround the source under analysis, provides a reasonable basis for developing screening estimates. There is a finite possibility that using fully developed CALMET input to CALPUFF, somewhat higher maxima might be simulated, but whether these would be at receptors of interest in the Class I area(s) is considered less likely. In fact, it is considered highly likely that lower pollutant impacts would be simulated if use was made of fully developed CALMET input to CALPUFF, and only impacts to receptors in the Class I area(s) were considered. The IWAQM recommends use of the new screening technique, as it provides a more realistic assessment of the fate and transport of the pollutants than the Phase 1 screening (Level 1) technique. The new screening technique provides estimates of maximum impacts, that are similar to those derived using fully developed CALMET input. Although, the air dispersion modeling community has less experience using the CALPUFF puff dispersion model than the ISC plume dispersion model, the operation of CALPUFF (with ISC meteorological input) is not anticipated to be unduly difficult or onerous.

Realistic expectations

At the Sixth Modeling Conference, some of the concerns expressed were that estimating pollutant impacts is so uncertain in some circumstances to perhaps preclude meaningful use of the estimated impacts. An example that was used to illustrate this point was described where the source emissions being characterized were separated from the receptors of interest by two mountain ridges, whose tops exceeded the effective release height of the example source. The situation described was neither impossible nor unrealistic. The IWAQM agrees with the commenter's conclusion that in such a situation highly uncertain pollutant impacts would be generated, regardless of the air quality model employed. Whether such estimates would be of little practical use would depend on the exact nature of the assessment being attempted. Even though the estimates might be uncertain and depend on the physics incorporated in the air dispersion model simulations, inspection of the simulation results might suggest that impacts from the source in question could reasonably be argued to be inconsequential or highly unlikely. As in any air quality simulation, the usefulness of the results obtained depends mostly on the expertise brought to the analysis in characterizing the situation, and on the experience applied in interpreting the results obtained. The IWAQM agrees with the sentiments of the commenters at the Sixth Modeling Conference, that as the terrain and land-use induced mesoscale circulations become more dominant, the expertise and integrity of the modeler will define the usefulness of the results.

It would be convenient if objective criteria could be developed that would identify when air quality simulation results are of questionable integrity. It would be convenient if objective criteria and "cookbook" procedures could be constructed that would preclude inappropriate application of air dispersion models. This has proved to be troublesome for local-scale modeling, and even more problematic for mesoscale and long-range transport modeling.

In response to the comments received, IWAQM has attempted to warn the modeling community in the summary of its Phase 2 recommendations (Section 2), that conducting a long-range transport assessment requires competent individuals. The IWAQM have also tried to warn the modeling community that application of the CALPUFF modeling system to any situation will require expert judgment, it will likely involve site-specific decisions, and it will require strong interaction and coordination with the applicable reviewing authorities.

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16. ABSTRACT

This Phase 2 Report is published by the Interagency Workgroup on Air Quality Modeling (IWAQM) in an effort to provide the sponsoring agencies and other interested parties information on appropriate “off-the-shelf” methods for estimating long range transport impacts of air pollutants on Federal Class I areas.

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U.S. Environmental Protection Agency
Office of Air Quality Planning and Standards
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PREFACE

This User's Guide for the AMS/EPA Regulatory Model (AERMOD) provides user instructions for the AERMOD model. The technical description of the AERMOD algorithms is provided in a separate document (EPA, 2004a). The revised AERMOD model described in this user's guide includes the following modifications and enhancements: the PRIME building downwash algorithms based on the ISC-PRIME model; use of allocatable arrays for data storage; incorporation of EVENT processing for analyzing short-term source culpability; post-1997 PM10 processing; a non-regulatory default TOXICS option that includes optimizations for area sources and the Sampled Chronological Input Model (SCIM) option; explicit treatment of multiple-year meteorological data files and the ANNUAL average; and options to specify emissions that vary by season, hour-of-day and day-of-week.

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1.0 INTRODUCTION

This section provides an overall introduction to the AERMOD model and to the AERMOD user's guide. Some suggestions are offered on how various users would best benefit from using the manuals. Also provided is an overview of the model's applicability, range of options, and basic input data and hardware requirements. The input file needed to run the AERMOD model is based on an approach that uses descriptive keywords and allows for a flexible structure and format.

1.1 HOW TO USE THE AERMOD MANUALS

The AERMOD model user's guide has been designed in an attempt to meet the needs of various types of users, depending on their level of experience with the model. This section describes briefly how different types of users would benefit most from their use of the manual.

1.1.1 Novice Users

Novice users are those whose exposure to or experience with the AERMOD model has been limited. They may be new to dispersion modeling applications in general, or new to the AERMOD model and therefore unfamiliar with the keyword/parameter approach utilized for the input file. These users should review the remainder of this Introduction to gain an overall perspective of the use of AERMOD model, particularly for regulatory modeling applications. They should then concentrate their review on Section 2, which provides a brief tutorial on setting up an input file that illustrates the most commonly used options of the AERMOD model. Section 2 provides a basic description of the input file structure and explains some of the advantages of the keyword/parameter approach to specifying modeling options and inputs. As the user becomes more familiar with the operation of the model and encounters the need to use more advanced features of the model, he/she will want to review the contents of Section 3, which provides a more detailed and complete reference of the

various options for running the model.

1.1.2 Experienced Modelers

Experienced modelers will have had considerable experience in applying the AERMOD model in a variety of situations. They should have basic familiarity with the overall goals and purposes of regulatory modeling in general, and with the scope of options available in the AERMOD model in particular. Experienced modelers who are new to the AERMOD model will benefit from first reviewing the contents of Section 2 of this volume, which will give them a basic orientation to the structure, organization and philosophy of the keyword/parameter approach used for the input runstream file. Once they have a basic grasp of the input file structure and syntax rules, they will benefit most from using Section 3 of this volume as a reference to learn the overall capabilities of the model, or to understand the mechanics for implementing particular options. The information in Section 3 has a functional organization with detailed descriptions of each of the individual keyword options by functional pathway. Once they are familiar with most or all of the keywords, they may find the functional keyword reference provided in Appendix B useful to quickly review the proper syntax and available options/parameters for a particular keyword. They may also find the Quick Reference available at the end of the user's guide sufficient as a simple reminder of the available keywords for each pathway and to ensure the proper order of parameters for each input image.

Experienced modelers may also need to refer to the description of model formulation for AERMOD (EPA, 2000) in order to gain a more complete understanding of the technical basis for the AERMOD model.

1.1.3 Management/Decision Makers

Those involved in a management or decision-making role for dispersion modeling applications will be especially interested in the remainder of this section, which provides an

overview of the model, including its role in various regulatory programs, a brief description of the range of available options, and basic input data and computer hardware requirements needed to run the model. From this information they should understand the basic capabilities of the AERMOD model well enough to judge the suitability of the model for particular applications. They may also want to review the brief tutorial provided in Section 2 to learn about the nature and structure of the input runstream file, in order to better be able to review the modeling results.

1.1.4 Programmers/Systems Analysts

Programmers and systems analysts, specifically those involved with installing the AERMOD code on other computer systems or charged with maintaining the code, should review the contents of Section 4 of this document. This will give specific details on compiling and linking the code for various situations, and explain in detail the memory storage requirements and control of input and output (I/O). They may also wish to review the remainder of this Introduction and the brief tutorial in Section 2 of this volume in order to have a basic understanding of the nature and overall capabilities of the model, and to understand the basic input runstream file structure and organization.

1.2 OVERVIEW OF THE AERMOD MODEL

This section provides an overview of the AERMOD model, including a discussion of the regulatory applicability of the model, a description of the basic options available for running the model, and an explanation of the basic input data and hardware requirements needed for executing the model.

1.2.1 Regulatory Applicability

The U.S. Environmental Protection Agency (EPA) maintains a *Guideline on Air Quality Models* (hereafter, Guideline), which is published as Appendix W to 40 CFR Part 51

(as revised). The Guideline provides the agency's guidance on regulatory applicability of air quality dispersion models in general. In general, regulatory modeling applications should be carried out in accordance with a modeling protocol that is reviewed and approved by the appropriate agency prior to conducting the modeling. The modeling protocol should identify the specific model, modeling options and input data to be used for a particular application.

1.2.2 Basic Input Data Requirements

One of the basic inputs to AERMOD is the runstream setup file which contains the selected modeling options, as well as source location and parameter data, receptor locations, meteorological data file specifications, and output options. Another type of basic type of input data needed to run the model is the meteorological data. AERMOD requires two types of meteorological data files, that are provided by the AERMET meteorological preprocessor program (EPA, 2004b). One file consists of surface scalar parameters, and the other file consists of vertical profiles of meteorological data. These meteorological data files are described briefly later in this section, and in more detail in Sections 2 and 3. For applications involving elevated terrain effects, the receptor and terrain data will need to be processed by the AERMAP terrain preprocessing program (EPA, 2004c) before input to the AERMOD model.

1.2.3 Computer Hardware Requirements

The current version of the AERMOD model was developed on an IBM-compatible PC, and has been designed to run on PCs with an 80386 or higher central processing unit (CPU) chip, a minimum of 2 MB of RAM, a math coprocessor, and MS-DOS Version 3.2 or higher. In order to handle the input data files (runstream setup and meteorology) and the output files, it is required that the system have a hard disk drive. The amount of storage space required on the hard disk for a particular application will depend greatly on the output options selected. Some of the optional output files of concentration data can be rather large. More information on output file products is provided in Sections 2 and 3.

1.2.4 Overview of Available Modeling Options

The AERMOD model includes a wide range of options for modeling air quality impacts of pollution sources, making it a popular choice among the modeling community for a variety of applications. The following sections provide a brief overview of the options available in the AERMOD model.

1.2.4.1 Dispersion Options.

Since the AERMOD model is especially designed to support the EPA's regulatory modeling programs, the regulatory modeling options will be the default mode of operation for the model. These options include the use of stack-tip downwash, and a routine for processing averages when calm winds or missing meteorological data occur. The model also includes non-default options for suppressing the use of stack-tip downwash, and to disable the date checking for non-sequential meteorological data files. The latter option is needed to facilitate evaluation of the model. The user can specify several short term averages to be calculated in a single run of the AERMOD model, as well as requesting the overall period (e.g. annual) averages.

1.2.4.2 Source Options.

The model is capable of handling multiple sources, including point, volume, and area source types. Line sources may also be modeled as a string of volume sources or as elongated area sources. Several source groups may be specified in a single run, with the source contributions combined for each group. This is particularly useful for PSD applications where combined impacts may be needed for a subset of the modeled background sources that consume increment, while the combined impacts from all background sources (and the permitted source) are needed to demonstrate compliance with the National Ambient Air Quality Standards (NAAQS). The model contain algorithms for modeling the effects of

aerodynamic downwash due to nearby buildings on point source emissions. AERMOD does include algorithms for modeling depositional effects on particulate emissions.

Source emission rates can be treated as constant throughout the modeling period, or may be varied by month, season, hour-of-day, or other optional periods of variation. These variable emission rate factors may be specified for a single source or for a group of sources. The user may also specify a separate file of hourly emission rates for some or all of the sources included in a particular model run.

1.2.4.3 Receptor Options.

The AERMOD model has considerable flexibility in the specification of receptor locations. The user has the capability of specifying multiple receptor networks in a single run, and may also mix Cartesian grid receptor networks and polar grid receptor networks in the same run. This is useful for applications where the user may need a coarse grid over the whole modeling domain, but a denser grid in the area of maximum expected impacts. There is also flexibility in specifying the location of the origin for polar receptors, other than the default origin at (0,0) in x,y, coordinates.

The user can input elevated receptor heights in order to model the effects of terrain above (or below) stack base, and may also specify receptor elevations above ground level to model flagpole receptors. There is no distinction in AERMOD between elevated terrain below release height and terrain above release height, as with earlier regulatory models that distinguished between simple terrain and complex terrain. For applications involving elevated terrain, the user must also input a hill height scale along with the receptor elevation. To facilitate the generation of hill height scales for AERMOD, a terrain preprocessor, called AERMAP, has been developed (EPA, 2004c).

1.2.4.4 Meteorology Options.

The AERMOD model utilizes a file of surface boundary layer parameters and a file of profile variables including wind speed, wind direction, and turbulence parameters. These two types of meteorological inputs are generated by the meteorological preprocessor for AERMOD, which is called AERMET (EPA, 2004b). Both of these meteorological input files are sequential ASCII files, and the model automatically recognizes the format generated by AERMET as the default format. The model will process all available meteorological data in the specified input file by default, but the user can easily specify selected days or ranges of days to process.

1.2.4.5 Output Options.

The basic types of printed output available with AERMOD are:

- Summaries of high values (highest, second highest, etc.) by receptor for each averaging period and source group combination;
- Summaries of overall maximum values (e.g., the maximum 50) for each averaging period and source group combination; and
- Tables of concurrent values summarized by receptor for each averaging period and source group combination for each day of data processed. These "raw" concentration values may also be output to unformatted (binary) files, as described below.

The tables by receptor and maximum value tables can be output for the source group values or for the individual source values, or both. In addition, when maximum values for individual sources are output, the user has the option of specifying whether the maximum source values are to be the maximum values for each source independently, or the contribution of each source to the maximum group values, or both.

In addition to the tabular printed output products described above, the AERMOD model provides options for several types of file output products. One of these options for

AERMOD is to output an unformatted ("binary") file of all concentration values as they are calculated. These files are often used for special postprocessing of the data. In addition to the unformatted concentration files, AERMOD provides options for two additional types of file outputs. One option is to generate a file of (X,Y) coordinates and design values (e.g., the second highest values at each receptor for a particular averaging period and source group combination) that can be easily imported into many graphics plotting packages to generate contour plots of the concentration values. Separate files can be specified for all of the averaging period and source group combinations of interest to the user.

Another output file option of the AERMOD model is to generate a file of all occurrences when a concentration value equals or exceeds a user-specified threshold. Again, separate files are generated for only those combinations of averaging period and source group that are of interest to the user. These files include the date on which the threshold violation occurred, the receptor location, and the concentration value.

AERMOD includes options for two types of output files that are designed to facilitate model evaluation. One type of file lists concentrations by rank, where only one value per date is included. This file may be used to generate Q-Q (quantile) plots of results, where values from different models and/or observed data are paired by rank. The other type of output file provides arc maxima results along with detailed information about the plume characteristics associated with the arc maximum.

1.2.4.6 Source Contribution Analyses.

In air quality dispersion modeling applications, the user may have a need to know the contribution that a particular source makes to an overall concentration value for a group of sources. This section provides a brief introduction to how these types of source contribution (sometimes referred to as source culpability) analyses are performed using the AERMOD model. More detailed information about exercising these options is provided in Section 3.

The AERMOD model provides the option of specifying source groups for which the model calculates high values independently. However, users may often have to run the model a second time selecting only specific days where the high values occurred, and setting up each source in its own source group in order to obtain source contribution results. Rather than running a separate EVENT model, as was done with ISCST2 (the original precursor to the AERMOD model), the EVENT processing has been incorporated into the AERMOD model.

2.0 GETTING STARTED - A BRIEF TUTORIAL

This section provides a brief tutorial for setting up a simple application problem with the AERMOD model, which serves as an introduction for novice users to the AERMOD model. The example illustrates the usage of the most commonly used options in the AERMOD model. A more complete description of the available options for setting up the AERMOD model is provided in Section 3.

The example problem presented in this section is a simple application of the AERMOD model to a single point source. The source is a hypothetical stack at a small isolated facility in a rural setting. Since the stack is below the Good Engineering Practice (GEP) stack height, the emissions from the source are subject to the influence of aerodynamic downwash due to the presence of nearby buildings. The tutorial leads the user through selection and specification of modeling options, specification of source parameters, definition of receptor locations, specification of the input meteorological data, and selection of output options. Since this discussion is aimed at novice users of the AERMOD model, a general description of the input file keyword/parameter approach is provided first.

2.1 DESCRIPTION OF KEYWORD/PARAMETER APPROACH

The input file for the AERMOD model makes use of a keyword/parameter approach to specifying the options and input data for running the model. The descriptive keywords and parameters that make up this input runstream file may be thought of as a command language through which the user communicates with the model what he/she wishes to accomplish for a particular model run. The keywords specify the type of option or input data being entered on each line of the input file, and the parameters following the keyword define the specific options selected or the actual input data. Some of the parameters are also input as descriptive secondary keywords.

The runstream file is divided into five functional "pathways." These pathways are identified by a two-character pathway ID placed at the beginning of each runstream image. The pathways and the order in which they are input to the model are as follows:

CO - for specifying overall job **CO**ntrol options;

SO - for specifying **SO**urce information;

RE - for specifying **RE**ceptor information;

ME - for specifying **ME**teorology information;

EV - for specifiying **EV**ent processing;

OU - for specifying **OU**tput options.

Each line of the input runstream file consists of a pathway ID, an 8-character keyword, and a parameter list. An example of a line of input from a runstream file, with its various parts identified, is shown below:

```
Column: 12345678901234567890123456789012345678901234567890123456789

        CO MODELOPT DFAULT  CONC
        |     |          |     |
        |     |          |     |
        |     |          |     |_____ Parameters
        |     |          |
        |     |_____________________ 8-Character Keyword
        |
        |_____________________________ 2-Character Pathway ID
```

The following sections describe the rules for structuring the input runstream file, and explain some of the advantages of the keyword/parameter approach.

2.1.1 Basic Rules for Structuring Input Runstream Files

While the input runstream file has been designed to provide the user with considerable flexibility in structuring the input file, there are some basic syntax rules that need to be followed. These rules serve to maintain some consistency between input files generated by

different users, to simplify the job of error handling performed by the model on the input data, and to provide information to the model in the appropriate order wherever order is critical to the interpretation of the inputs. These basic rules and the various elements of the input runstream file are described in the paragraphs that follow.

One of the most basic rules is that all inputs for a particular pathway must be contiguous, i.e., all inputs for the CO pathway must come first, followed by the inputs for the SO pathway, and so on. The beginning of each pathway is identified with a "STARTING" keyword, and the ending of the pathway with the "FINISHED" keyword. Thus the first functional record of each input file must be "CO STARTING" and the last record of each input file must be "OU FINISHED." The rest of the input images will define the options and input data for a particular run.

Each record in the input runstream file is referred to as a runstream "image." These records are initially read into the model as 132-character images. The information on each input image consists of a "pathway," a "keyword," and one or more "parameters." Each of these "fields" on the runstream image must be separated from other fields by at least one blank space. To simplify the interpretation of the runstream image by the model, the runstream file must be structured with the two-character pathway in columns 1 and 2, the eight-character keyword in columns 4 through 11, followed by the parameters in columns 13 through 132, as necessary. For most keywords, the <u>order</u> of parameters following the keyword <u>is</u> important -- the exact <u>spacing</u> of the parameters <u>is not</u> important, as long as they are separated from each other by at least one blank space and do not extend beyond the 132 character limit. The example of a runstream image from the CO pathway shown above is repeated here:

```
Column: 1234567890123456789012345678901234567890123456789012345678901234567890123456789

        CO MODELOPT DFAULT  CONC
        |    |        |      |
        |    |        |______|______________ Parameters
        |    |
        |    |_______________________________ 8-Character Keyword
        |
        |____________________________________ 2-Character Pathway ID
```

Alphabetical characters can be input as either lower case or upper case letters. The model convert all character input to upper case letters internally, with the exception of the title fields and file names to be discussed later. Throughout this document, the convention of using upper case letters is followed. For numeric input data, it should be noted that all data are assumed to be in metric units, i.e., length units of meters, speed units of meters per second, temperature units of degrees Kelvin, and emission units of grams per second. In a few instances, the user has the option of specifying units of feet for length and the model will perform the conversion to meters. These exceptions are the input of receptor heights for elevated terrain and the specification of anemometer height, since these values are often more readily available in feet than in meters.

Certain keywords are mandatory and must be present in every runstream file, such as the MODELOPT keyword shown in the example above which identifies the modeling options. Other keywords are optional and are only needed to exercise particular options, such as the option to allow for the input of flagpole receptor heights. Some of the keywords are repeatable, such as the keywords to specify source parameters, while other keywords may only appear once. The keyword references in Section 3, Appendices A and B and the Quick Reference at the end of this volume identify each keyword as to its type, either mandatory or optional, and either repeatable or non-repeatable.

With a few exceptions that are described below, the order of keywords within each pathway is not critical. For the SO pathway, the LOCATION keyword must be specified before other keywords for a particular source, and the SRCGROUP keyword must be the last

keyword before SO FINISHED. For keywords on the SO pathway that accept a range of source IDs, the source parameters specified by those keywords will only be applied to the sources already defined, and will exclude any sources that are specified latter in the input file.

The PARAMETER ILEN_FLD is used to specify the maximum length of individual fields on the input runstream image, and also to declare the length of all filename and format variables. This PARAMETER is initially assigned a value of 80, and is in MODULE MAIN1 in MODULES.FOR.

2.1.2 Advantages of the Keyword Approach

The keyword approach provides some advantages over the type of input file used by other models that require formatted input of several numeric switches. One advantage is that the keywords are descriptive of the options and inputs being used for a particular run, making it easier for a reviewer to ascertain what was accomplished in a particular run by reviewing the input file. Another advantage is that the user has considerable flexibility in structuring the inputs to improve their readability and understandability, as long as they adhere to the few basic rules described above.

Some special provisions have been made to increase the flexibility to the user in structuring the input files. One provision is to allow for blank records in the input file. This allows the user to separate the pathways from each other, or to separate a group of images, such as source locations, from the other images. Another provision is for the use of "comment lines," identified by a "**" in the pathway field. Any input image that has "**" for the pathway ID will be ignored by the model. This is especially useful for labeling the columns in the source parameter input images, as illustrated in the example problem later in this section. It may also be used to "comment out" certain options for a particular run without deleting the options and associated data (e.g., elevated terrain heights) completely from the input file. Because of the descriptive nature of the keyword options and the flexibility of the

inputs it is generally much easier to make modifications to an existing input runstream file to obtain the desired result.

Another reason for improved "user-friendliness" is that detailed error-handling has been built into the model. The model provides descriptions of the location and nature of all of the errors encountered for a particular run. Rather than stopping execution at each occurrence of an input error, the model will read through and attempt to process all input records and report all errors encountered. If a fatal error occurs, then the model will not attempt to execute the model calculations.

2.2 REGULATORY MODELING OPTIONS

The regulatory default option is controlled from the MODELOPT keyword on the CO pathway. As its name implies, this keyword controls the selection of modeling options. It is a mandatory, non-repeatable keyword, and it is an especially important keyword for understanding and controlling the operation of the AERMOD model. Unless specified otherwise through the available keyword options, the AERMOD model implements the following default options:

- Use the elevated terrain algorithms requiring input of terrain height data;
- Use stack-tip downwash (except for building downwash cases);
- Use the calms processing routines;
- Use the missing data processing routines;
- Use a 4-hour half life for exponential decay of SO_2 for urban sources.

The parameters used to specify options on the MODELOPT keyword are character strings, called "secondary keywords," that are descriptive of the option being selected. For example, to ensure that the regulatory default options are used for a particular run, the user would include the secondary keyword "DFAULT" on the MODELOPT input. The presence of this

secondary keyword tells the model to override any attempt to use a non-regulatory default option. The model will warn the user if a non-regulatory option is selected along with the DFAULT option, but will not halt processing. For regulatory modeling applications, it is strongly suggested that the DFAULT switch be set, even though the model defaults to the regulatory options without it. The MODELOPT keyword is described in more detail in the Section 3.2.2.

For any application in which a non-regulatory option is to be selected, the DFAULT switch must not be set, since it would otherwise override the non-regulatory option. The non-regulatory options are also specified by descriptive secondary keywords; for example, "NOSTD" invokes the option not to use stack-tip downwash.

2.3 MODEL STORAGE LIMITS

The AERMOD model has been designed using a dynamic storage allocation approach, where the model allocates data storage as needed based on the number of sources, receptors, source groups, and input requirements, up to the maximum amount of memory available on the computer being used.

The AERMOD model uses dynamic arrays to allocate data storage at model runtime rather than at compile time, as done by the previous version of AERMOD. The AERMOD model preprocesses the model runstream input file to determine the data storage requirements for a particular model run, and then allocates the input data arrays before processing the setup data. Once the setup processing is completed, the model allocates storage for the result arrays. When allocating data storage, the AERMOD model traps for errors, e.g., not enough memory available to allocate. If the allocation is unsuccessful, then an error message is generated by the model and further processing is prevented. If the CO RUNORNOT NOT option is selected, the model will still go through all array allocations so that the user can determine if sufficient memory is available to complete the run. Also, an estimate of the total

amount of memory needed for a particular run is printed out as part of the first page of printed output.

The parameters that are established at model runtime are as follows:

NSRC	= Number of Sources
NREC	= Number of Receptors
NGRP	= Number of Source Groups
NAVE	= Number of Short Term Averaging Periods
NVAL	= Number of High Values by Receptor (RECTABLE Keyword)
NTYP	= Number of Output Types (CONC currently is the only output type)
NMAX	= Number of Overall Maximum Values (MAXTABLE Keyword)
NQF	= Number of Variable Emission Rate Factors Per Source
NPDMAX	= Number of Particle Diameter Categories Per Source
IXM	= Number of X-coord (Distance) Values Per Receptor Network
IYM	= Number of Y-coord (Direction) Values Per Receptor Network
NNET	= Number of Cartesian and/or Polar Receptor Networks
NARC	= Number of Receptor Arcs Used with EVALCART Keyword
NEVE	= Number of Events for EVENT processing

In the case of NPDMAX, if no particle information is present in the input runstream, then NPDMAX is set to 1, otherwise it is set to 20. Other parameters are set to the actual numbers required for a particular model run.

There are several static array limits defined in AERMOD. These limits are controlled by PARAMETER statements in the Fortran source code. The variable name, description, and current value are defined in Section 4.2.2. If any of these static limits are changed, then AERMOD must be recompiled and linked. This process is described in Section 4.2.1.

2.4 SETTING UP A SIMPLE RUNSTREAM FILE

This section goes through a step-by-step description of setting up a simple application problem, illustrating the most commonly used options of the AERMOD model. The example problem is based on a simple industrial source application. The input file for AERMOD for the example problem is shown in Figure 2-1. The remainder of this section explains the various parts of the input file for the AERMOD model, and also illustrates some of the flexibility in structuring the input file.

```
CO STARTING
CO TITLEONE  A Simple Example Problem for the AERMOD-PRIME Model
CO MODELOPT  CONC   FLAT
CO AVERTIME  3  24  PERIOD
CO POLLUTID  SO2
CO RUNORNOT  RUN
CO FINISHED

SO STARTING
SO LOCATION  STACK1  POINT  0.0   0.0   0.0
SO SRCPARAM  STACK1  500.0   65.00  425.  15.0   5.
SO BUILDHGT  STACK1    36*50.
SO BUILDWID  STACK1    62.26   72.64   80.80   86.51   89.59   89.95
SO BUILDWID  STACK1    87.58   82.54   75.00   82.54   87.58   89.95
SO BUILDWID  STACK1    89.59   86.51   80.80   72.64   62.26   50.00
SO BUILDWID  STACK1    62.26   72.64   80.80   86.51   89.59   89.95
SO BUILDWID  STACK1    87.58   82.54   75.00   82.54   87.58   89.95
SO BUILDWID  STACK1    89.59   86.51   80.80   72.64   62.26   50.00
SO BUILDLEN  STACK1    82.54   87.58   89.95   89.59   86.51   80.80
SO BUILDLEN  STACK1    72.64   62.26   50.00   62.26   72.64   80.80
SO BUILDLEN  STACK1    86.51   89.59   89.95   87.58   82.54   75.00
SO BUILDLEN  STACK1    82.54   87.58   89.95   89.59   86.51   80.80
SO BUILDLEN  STACK1    72.64   62.26   50.00   62.26   72.64   80.80
SO BUILDLEN  STACK1    86.51   89.59   89.95   87.58   82.54   75.00
SO XBADJ     STACK1   -47.35  -55.76  -62.48  -67.29  -70.07  -70.71
SO XBADJ     STACK1   -69.21  -65.60  -60.00  -65.60  -69.21  -70.71
SO XBADJ     STACK1   -70.07  -67.29  -62.48  -55.76  -47.35  -37.50
SO XBADJ     STACK1   -35.19  -31.82  -27.48  -22.30  -16.44  -10.09
SO XBADJ     STACK1    -3.43    3.34   10.00    3.34   -3.43  -10.09
SO XBADJ     STACK1   -16.44  -22.30  -27.48  -31.82  -35.19  -37.50
SO YBADJ     STACK1    34.47   32.89   30.31   26.81   22.50   17.50
SO YBADJ     STACK1    11.97    6.08    0.00   -6.08  -11.97  -17.50
SO YBADJ     STACK1   -22.50  -26.81  -30.31  -32.89  -34.47  -35.00
SO YBADJ     STACK1   -34.47  -32.89  -30.31  -26.81  -22.50  -17.50
SO YBADJ     STACK1   -11.97   -6.08    0.00    6.08   11.97   17.50
SO YBADJ     STACK1    22.50   26.81   30.31   32.89   34.47   35.00
SO SRCGROUP  ALL
SO FINISHED

RE STARTING
RE GRIDPOLR POL1 STA
RE GRIDPOLR POL1 ORIG STACK1
RE GRIDPOLR POL1 DIST 175. 350. 500. 1000.
RE GRIDPOLR POL1 GDIR 36 10 10
RE GRIDPOLR POL1 END
RE FINISHED

ME STARTING
ME SURFFILE  AERMET2.SFC
ME PROFFILE  AERMET2.PFL
ME SURFDATA  14735  1988  ALBANY,NY
ME UAIRDATA  14735  1988  ALBANY,NY
ME PROBATE  0.0  METERS
ME FINISHED

OF STARTING
OF RECTABLE  ALIVE  FIRST-SECOND
OF MAXTABLE  ALIVE  50
OF FINISHED
```

FIGURE 2-1. EXAMPLE INPUT FILE FOR AERMOD FOR SAMPLE PROBLEM

2.4.1 A Simple Industrial Source Application

For this simple tutorial, an application is selected involving a single point source of SO_2 that is subject to the influences of building downwash. The source consists of a 50-meter stack with a buoyant release that is adjacent to a building. We will assume that the stack is situated in flat terrain in a rural setting. A polar receptor network will be placed around the stack location to identify areas of maximum impact.

2.4.2 Selecting Modeling Options - CO Pathway

The modeling options are input to the model on the Control pathway. The mandatory keywords for the CO pathway are listed below. A complete listing of all keywords is provided in Appendix B.

STARTING - Indicates the beginning of inputs for the pathway; this keyword is mandatory on each of the pathways.

TITLEONE - A user-specified title line (up to 68 characters) that will appear on each page of the printed output file (an optional second title line is also available with the keyword TITLE TWO).

MODELOPT - Controls the modeling options selected for a particular run through a series of secondary keywords.

AVERTIME - Identifies the averaging periods to be calculated for a particular run.

POLLUTID - Identifies the type of pollutant being modeled. At the present time, this option has no influence on the results.

RUNORNOT - A special keyword that tells the model whether to run the full model executions or not. If the user selects not to run, then the runstream setup file will be processed and any input errors reported, but no dispersion calculations will be made.

FINISHED - Indicates that the user is finished with the inputs for this pathway; this keyword is also mandatory on each of the other pathways.

The first two keywords are fairly self-explanatory. As discussed above in Section 2.2, the MODELOPT keyword on the CO pathway is pivotal to controlling the modeling options used for a particular run. For this example, we intend to use the regulatory default option, and have specified for the model to output concentration values. After the first three input records our input file will look something like this:

```
CO STARTING
CO TITLEONE  A Simple Example Problem for the AERMOD-PRIME Model
CO MODELOPT  CONC FLAT
```

Note that the title parameter field does not need to be in quotations, even though it represents a single parameter. The model simply reads whatever appears in columns 13 through 80 of the TITLEONE card as the title field, without changing the lower case to upper case letters. Leading blanks are therefore significant if the user wishes to center the title within the field. Note also that the spacing and order of the secondary keywords on the MODELOPT card are not significant. A MODELOPT card that looked like this:

```
CO MODELOPT   CONC              FLAT
```

would have an identical result as the example above. It is suggested that the user adopt a style that is consistent and easy to read. A complete description of the available modeling options that can be specified on the MODELOPT keyword is provided in Section 3.

Since the pollutant in this example is SO_2, we will probably need to calculate average values for 3-hour and 24-hour time periods, and we also need to calculate averages for the full

annual time period. Our runstream file might therefore look something like this after adding two more keywords:

```
CO STARTING
CO TITLEONE  A Simple Example Problem for the AERMOD-PRIME Model
CO MODELOPT  CONC FLAT
CO AVERTIME  3  24  PERIOD
CO POLLUTID  SO2
```

Note again that the order of the parameters on the AVERTIME keyword is not critical, although the order of the short term averages given on the AVERTIME keyword will also be the order in which the results are presented in the output file. The order of the keywords within each pathway is also not critical in most cases, although the intent of the input runstream file may be easier to decipher if a consistent and logical order is followed. It is suggested that users follow the order in which the keywords are presented in Section 3, in Appendix B, and in the Quick Reference, unless there is a clear advantage to doing otherwise.

The only remaining mandatory keywords for the CO pathway are RUNORNOT and FINISHED. We will set the RUNORNOT switch to RUN for this example. If a user is unsure about the operation of certain options, or is setting up a complex runstream file to run for the first time, it may be desirable to set the model NOT to run, but simply to read and analyze the input file and report any errors or warning messages that are generated. Once the input file has been debugged using these descriptive error/warning messages, then the RUNORNOT switch can be set to RUN, avoiding a possible costly waste of resources generating erroneous results. Even if the model is set NOT to run, all of the inputs are summarized in the output file for the user to review.

Our complete runstream file for the CO pathway may look something like this:

```
CO STARTING
CO TITLEONE  A Simple Example Problem for the AERMOD-PRIME Model
CO MODELOPT  CONC FLAT
CO AVERTIME  3  24  PERIOD
CO POLLUTID  SO2
CO RUNORNOT  RUN
CO FINISHED
```

The following set of runstream images has a more structured look, but it is equivalent to the example above:

```
CO STARTING
   TITLEONE  A Simple Example Problem for the AERMOD-PRIME Model
   MODELOPT  CONC FLAT
   AVERTIME  3  24  PERIOD
   POLLUTID  SO2
   RUNORNOT  RUN
CO FINISHED
```

Since the pathway ID is required to begin in column 1 (see Section 2.4.8 for a discussion of this restriction), the model will assume that the previous pathway is in effect if the pathway field is left blank. The model will do the same for blank keyword fields, which will be illustrated in the next section.

In addition to these mandatory keywords on the CO pathway, the user may select optional keywords to allow the use of receptor heights above ground-level for flagpole receptors, to specify a decay coefficient or a half-life for exponential decay, and to generate an input file containing events for EVENT processing. The user also has the option of having the model periodically save the results to a file for later re-starting in the event of a power failure or other interruption of the model's execution. These options are described in more detail in Section 3 of this volume.

2.4.3 Specifying Source Inputs - SO Pathway

Besides the STARTING and FINISHED keywords that are mandatory for all pathways, the Source pathway has the following mandatory keywords:

LOCATION - Identifies a particular source ID and specifies the source type and location of that source.

SRCPARAM - Specifies the source parameters for a particular source ID identified by a previous LOCATION card.

SRCGROUP - Specifies how sources will be grouped for calculational purposes. There is always at least one group, even though it may be the group of ALL sources and even if there is only one source.

Since the hypothetical source in our example problem is influenced by a nearby building, we also need to include the optional keywords BUILDHGT and BUILDWID in our input file.

The input file for the SO pathway for this example will look something like this:

```
SO STARTING
SO LOCATION  STACK1  POINT  0.0   0.0   0.0
SO SRCPARAM  STACK1  500.0   65.00  425.  15.0   5.0
SO BUILDHGT  STACK1    50.00   50.00   50.00   50.00   50.00   50.00
SO BUILDHGT  STACK1    50.00   50.00   50.00   50.00   50.00   50.00
SO BUILDHGT  STACK1    50.00   50.00   50.00   50.00   50.00   50.00
SO BUILDHGT  STACK1    50.00   50.00   50.00   50.00   50.00   50.00
SO BUILDHGT  STACK1    50.00   50.00   50.00   50.00   50.00   50.00
SO BUILDHGT  STACK1    50.00   50.00   50.00   50.00   50.00   50.00
SO BUILDWID  STACK1    62.26   72.64   80.80   86.51   89.59   89.95
SO BUILDWID  STACK1    87.58   82.54   75.00   82.54   87.58   89.95
SO BUILDWID  STACK1    89.59   86.51   80.80   72.64   62.26   50.00
SO BUILDWID  STACK1    62.26   72.64   80.80   86.51   89.59   89.95
SO BUILDWID  STACK1    87.58   82.54   75.00   82.54   87.58   89.95
SO BUILDWID  STACK1    89.59   86.51   80.80   72.64   62.26   50.00
SO BUILDLEN  STACK1    82.54   87.58   89.95   89.59   86.51   80.80
SO BUILDLEN  STACK1    72.64   62.26   50.00   62.26   72.64   80.80
SO BUILDLEN  STACK1    86.51   89.59   89.95   87.58   82.54   75.00
SO BUILDLEN  STACK1    82.54   87.58   89.95   89.59   86.51   80.80
SO BUILDLEN  STACK1    72.64   62.26   50.00   62.26   72.64   80.80
SO BUILDLEN  STACK1    86.51   89.59   89.95   87.58   82.54   75.00
SO XBADJ     STACK1   -47.35  -55.76  -62.48  -67.29  -70.07  -70.71
SO XBADJ     STACK1   -69.21  -65.60  -60.00  -65.60  -69.21  -70.71
SO XBADJ     STACK1   -70.07  -67.29  -62.48  -55.76  -47.35  -37.50
SO XBADJ     STACK1   -35.19  -31.82  -27.48  -22.30  -16.44  -10.09
SO XBADJ     STACK1    -3.43    3.34   10.00    3.34   -3.43  -10.09
SO XBADJ     STACK1   -16.44  -22.30  -27.48  -31.82  -35.19  -37.50
SO YBADJ     STACK1    34.47   32.89   30.31   26.81   22.50   17.50
SO YBADJ     STACK1    11.97    6.08    0.00   -6.08  -11.97  -17.50
SO YBADJ     STACK1   -22.50  -26.81  -30.31  -32.89  -34.47  -35.00
SO YBADJ     STACK1   -34.47  -32.89  -30.31  -26.81  -22.50  -17.50
SO YBADJ     STACK1   -11.97   -6.08    0.00    6.08   11.97   17.50
SO YBADJ     STACK1    22.50   26.81   30.31   32.89   34.47   35.00
SO SRCGROUP  ALL
SO FINISHED
```

There are a few things to note about these inputs. Firstly, the source ID (STACK1 in this example) is an alphanumeric parameter (up to eight characters) that identifies the inputs for different keywords with a particular source. It is crucial that the source be identified with a LOCATION card before any other keyword makes reference to that source, since this identifies the source type (POINT in this case), and therefore which parameters the model will allow. Besides POINT sources, the current version of the AERMOD model also allows VOLUME and AREA sources to be specified. Since the effects of elevated terrain are included in this analysis, it is important to specify the source base elevation above mean sea level (MSL) on the LOCATION card. For this example, the source base elevation is 0.0 meters MSL.

Another thing to note is that since the model uses direction-specific building dimensions for all sources with downwash, there are 36 building heights and 36 building widths entered on the appropriate keywords, one value for each 10 degree sector beginning with the 10 degree flow vector (direction toward which the wind is blowing), and continuing clockwise. Since the user could not fit all 36 values on a single record, the pathway, keyword and source ID were repeated as many times as were necessary. In this case there were 6 values given on each of 6 lines for each of the building dimensions. There could have been fewer or more lines as long as exactly 36 values were entered before starting with a new keyword. Since all of the building heights were the same across the sectors (fairly realistic for the height but not for widths, unless the structure was circular), there is a short cut available for specifying numeric input in the runstream files for the model. The user can specify "repeat values" by entering a field such as "36*50.0" as a parameter for the BUILDHGT keyword. The model will interpret this as "36 separate entries, each with a value of 50.0," and store the values in the appropriate arrays within the model. Since the model must identify this as a single parameter field, there must not be any spaces between the repeat-value and the value to be repeated.

The final keyword before finishing the SO pathway must be the SRCGROUP keyword. In this example, since there is only one source, we have taken advantage of a short cut provided by the model by specifying a source group ID (which may be up to eight characters) of ALL. Whenever this card appears in an input file, it will generate a source group with a source-group ID of ALL, consisting of all sources defined for that run. The sources do not have to be explicitly identified. In a run involving multiple sources, the user may specify multiple source groups by repeating the SRCGROUP keyword. The use of the SRCGROUP card is explained in more detail in Section 3.

Using some of the formatting options discussed above, the SO pathway for our example may look like this, with the same result as above:

```
SO STARTING
   LOCATION  STACK1  POINT  0.0   0.0   0.0

** Point Source       QS     HS    TS    VS   DS
** Parameters:       ----   ----  ----  ----  ---
   SRCPARAM  STACK1  500.0  65.0  425.  15.0  5.0

   BUILDHGT  STACK1  36*50.
SO BUILDWID  STACK1    62.26   72.64   80.80   86.51   89.59   89.95
             STACK1    87.58   82.54   75.00   82.54   87.58   89.95
             STACK1    89.59   86.51   80.80   72.64   62.26   50.00
             STACK1    62.26   72.64   80.80   86.51   89.59   89.95
             STACK1    87.58   82.54   75.00   82.54   87.58   89.95
             STACK1    89.59   86.51   80.80   72.64   62.26   50.00
SO BUILDLEN  STACK1    82.54   87.58   89.95   89.59   86.51   80.80
             STACK1    72.64   62.26   50.00   62.26   72.64   80.80
             STACK1    86.51   89.59   89.95   87.58   82.54   75.00
             STACK1    82.54   87.58   89.95   89.59   86.51   80.80
             STACK1    72.64   62.26   50.00   62.26   72.64   80.80
             STACK1    86.51   89.59   89.95   87.58   82.54   75.00
SO XBADJ     STACK1   -47.35  -55.76  -62.48  -67.29  -70.07  -70.71
             STACK1   -69.21  -65.60  -60.00  -65.60  -69.21  -70.71
             STACK1   -70.07  -67.29  -62.48  -55.76  -47.35  -37.50
             STACK1   -35.19  -31.82  -27.48  -22.30  -16.44  -10.09
             STACK1    -3.43    3.34   10.00    3.34   -3.43  -10.09
             STACK1   -16.44  -22.30  -27.48  -31.82  -35.19  -37.50
SO YBADJ     STACK1    34.47   32.89   30.31   26.81   22.50   17.50
             STACK1    11.97    6.08    0.00   -6.08  -11.97  -17.50
             STACK1   -22.50  -26.81  -30.31  -32.89  -34.47  -35.00
             STACK1   -34.47  -32.89  -30.31  -26.81  -22.50  -17.50
             STACK1   -11.97   -6.08    0.00    6.08   11.97   17.50
             STACK1    22.50   26.81   30.31   32.89   34.47   35.00
SRCGROUP  ALL
SO FINISHED
```

This version of the SO pathway inputs illustrates the use of the comment card to label the stack parameters on the SRCPARAM card, i.e., QS for emission rate (g/s), HS for stack height (m), TS for stack exit temperature (K), VS for exit velocity (m/s), and DS for stack diameter (m). A complete description of the source parameter card, with a list of parameters for each source type, is provided in Section 3.3 and in Appendix B.

Other optional inputs that may be entered on the SO pathway include specifying variable emission rate factors for sources whose emissions vary as a function of month, season, hour-of-day, or season <u>and</u> hour-of-day (see Section 3.3.4 for more details). The

number of factors entered depends on the option selected, and factors may be input for single sources or for a range of sources.

2.4.4 Specifying a Receptor Network - RE Pathway

As mentioned above, this example will illustrate the use of a single polar receptor network centered on the stack location. Other options available on the REceptor pathway include specifying a Cartesian grid receptor network, and specifying discrete receptor locations in either a polar or a Cartesian system. These other options are described in more detail in Section 3.4.

The RE pathway for this example will look like this:

```
RE STARTING
   GRIDPOLR POL1 STA
   GRIDPOLR POL1 ORIG STACK1
   GRIDPOLR POL1 DIST 175. 350. 500. 1000.
   GRIDPOLR POL1 GDIR 36 10 10
   GRIDPOLR POL1 END
RE FINISHED
```

Looking at the example for the RE pathway, the first thing to note about these inputs is that there is a new set of keywords, including something that looks like a STArting and ENDing. In fact the GRIDPOLR keyword can be thought of as a "sub-pathway," in that all of the information for a particular polar network must be in contiguous records, and that the starting and ending of the sub-pathway are identified. The order of secondary keywords within the sub-pathway is not critical, similar to the main pathways. Each card must be identified with a network ID (up to eight alphanumeric characters), in this case it is "POL1." Multiple networks may be specified in a single model run. The model waits until the END secondary keyword is encountered to set the variables, which may include terrain heights for receptors on elevated terrain or flagpole receptor heights if those options are being exercised

by the user. The use of these optional secondary keywords is described in detail in Section 3.4.

For this example, the ORIG secondary keyword specifies the location of the origin for the polar network being defined as being the location of the source STACK1. The origin can also be specified as X and Y-coordinates. The ORIG keyword is optional, and the model will default to an origin of (0.0, 0.0) if it is omitted. The DIST keyword identifies the distances along each direction radial at which the receptors will be located. In this case there are four distances. More distances could be added by adding values to that input card or by including a continuation card with the DIST keyword, if needed. The GDIR keyword specifies that the model will Generate DIRection radials for the network, in this case there will be 36 directions, beginning with the 10 degree flow vector and incrementing every 10 degrees clockwise. The user may elect to define Discrete DIRection radials instead by using the DDIR keyword in place of the GDIR keyword.

2.4.5 Specifying the Meteorological Input - ME Pathway

The MEteorology pathway has the following four mandatory keywords (besides STARTING and FINISHED, of course):

SURFFILE - Specifies the filename and format for the input surface meteorological data file.

PROFFILE - Specifies the filename and format for the input profile meteorological data file.

SURFDATA - Specifies information about the surface meteorological data which will be used in the modeling.

UAIRDATA - Specifies information about the upper air meteorological data which will be used in the modeling.

PROFBASE - Specifies the base elevation above MSL for the potential temperature profile.

For the purposes of this example we will assume that the meteorological data files are for Albany, NY and that an on-site location called Hudson has also been used. We will also assume that the surface and profile data files were generated by the AERMET preprocessor, and are in the default format for AERMOD. The filename of the surface file is AERMET2.SFC and it consist of four days of data for Albany/Hudson from March 1988. The filename of the profile file is AERMET2.PFL. The data files used in this example correspond with the on-site example files used for the AERMET preprocessor program. The runstream images for the MEteorology pathway would look something like this:

```
ME STARTING
   SURFFILE  AERMET2.SFC
   PROFFILE  AERMET2.PFL
   SURFDATA  14735  1988  ALBANY,NY
   UAIRDATA  14735  1988  ALBANY,NY
   SITEDATA  99999 1988   HUDSON
   PROFBASE  0.0  METERS
ME FINISHED
```

The first parameters on the SURFFILE and PROFFILE keywords are the filenames for the surface and profile data file, respectively, which can be entered as a full DOS pathname, including the drive specification and subdirectories, up to a total of 80 characters (with the maximum number of characters controlled by the ILEN_FLD PARAMETER located in MODULE MAIN1 - see Section 2.1.1). Since there is no second parameter, the model will assume the default ASCII format for the data files. The format of the surface and profile data files is described in Appendix D.

The next two mandatory inputs identify the location and data period of the input meteorological data. A separate keyword is used for the surface meteorological data and for the upper air (mixing height) data. The parameters on these cards are the station number (e.g. WBAN number for NWS stations), the data period (year), and a station name. In order to identify potential errors in the model inputs, the model compares the station number from the runstream input file with values provided in the first record of the surface meteorology file, and issues warning messages if there are any mismatches. The user may also optionally input

the (X,Y) coordinates for the location of the station(s), although these values are not currently used by the model. In this case, we have also included the optional SITEDATA keyword to identify the location for the on-site meteorological data that were preprocessed by AERMET.

The final mandatory keyword is PROFBASE, which is used to specify the base elevation (above MSL) for the potential temperature profile generated by AERMOD for use in the plume rise calculations. This should correspond to the base elevation for the main meteorological tower, which in this example is specified as 0.0 meters and is the same as the source base elevation.

Other optional keywords available on the ME pathway provide the user with options to specify selected days to process from the meteorological data file, and a wind direction rotation correction term. These optional inputs are described in more detail in Section 3.5.

2.4.6 Selecting Output Options - OU Pathway

All of the keywords on the Output pathway are optional, although the model will warn the user if no printed outputs are requested and will halt processing if no outputs (printed results or file outputs) are selected. The user has considerable flexibility to select only the outputs that are needed for a particular application. The printed table keywords are:

RECTABLE - Specifies the selection of high value by receptor table output options.

MAXTABLE - Specifies the selection of overall maximum value table output options.

DAYTABLE - Specifies the selection of printed results (by receptor) for each day of data processed (this option can produce very large files and such be used with care).

The RECTABLE keyword provides the highest, second-highest and third-highest values by receptor. The MAXTABLE keyword provides the overall maximum 50 table. For both of these keywords, the user has additional flexibility to specify for which short term averaging periods the outputs are selected. For the MAXTABLE keyword the user can also

specify the number of overall maximum values to summarize for each averaging period selected, up to a maximum number controlled by a parameter in the computer code. For this example problem we will select the highest and second-highest values by receptor, and the maximum 50 values for all averaging periods. These OU pathway inputs will look something like this:

```
OU STARTING
   RECTABLE  ALLAVE  FIRST  SECOND
   MAXTABLE  ALLAVE  50
OU FINISHED
```

To simplify the input for users who request the same printed table output options for all averaging periods, these keywords recognize the secondary keyword "ALLAVE" as the first parameter for that purpose. In order to obtain the overall maximum 10 values for the 24-hour averages only, then the OU pathway images would look like this:

```
OU STARTING
   RECTABLE  ALLAVE  FIRST  SECOND
   MAXTABLE  24  10
OU FINISHED
```

It should also be noted that these output table options apply only to the short-term averaging periods, such as the 3-hour and 24-hour averages used in our example. If the user has selected that PERIOD averages be calculated (on the CO AVERTIME keyword), then the output file will automatically include a table of period averages summarized by receptor (the RECTABLE option does not apply since there is only one period value for each receptor). In addition, the printed output file will include tables summarizing the highest values for each averaging period and source group.

Other options on the OU pathway include several keywords to produce output files for specialized purposes, such as generating contour plots of high values, identifying occurrences

of violations of a particular threshold value (e.g. a NAAQS), and for postprocessing of the raw concentration data. These options are described in detail in Section 3.7.

The complete input runstream file for this simple example is shown in Figure 2-2. Note that a consistent style has been used for formatting and structuring the file in order to improve its readability. This input file is comparable to the version shown earlier in Figure 2-1, which used a somewhat different style.

```
CO STARTING
   TITLEONE A Simple Example Problem for the AERMOD Model
   MODELOPT  DFAULT  CONC
   AVERTIME  3  24  PERIOD
   POLLUTID  SO2
   RUNORNOT  RUN
CO FINISHED

SO STARTING
   LOCATION  STACK1  POINT  0.0   0.0   0.0
** Point Source       QS     HS    TS    VS   DS
** Parameters:       ----   ----  ----  ----  ---
   SRCPARAM  STACK1  500.0  65.0  425.  15.0  5.0
   BUILDHGT  STACK1  36*50.
SO BUILDWID  STACK1    62.26   72.64   80.80   86.51   89.59   89.95
             STACK1    87.58   82.54   75.00   82.54   87.58   89.95
             STACK1    89.59   86.51   80.80   72.64   62.26   50.00
             STACK1    62.26   72.64   80.80   86.51   89.59   89.95
             STACK1    87.58   82.54   75.00   82.54   87.58   89.95
             STACK1    89.59   86.51   80.80   72.64   62.26   50.00
SO BUILDLEN  STACK1    82.54   87.58   89.95   89.59   86.51   80.80
             STACK1    72.64   62.26   50.00   62.26   72.64   80.80
             STACK1    86.51   89.59   89.95   87.58   82.54   75.00
             STACK1    82.54   87.58   89.95   89.59   86.51   80.80
             STACK1    72.64   62.26   50.00   62.26   72.64   80.80
             STACK1    86.51   89.59   89.95   87.58   82.54   75.00
SO XBADJ     STACK1   -47.35  -55.76  -62.48  -67.29  -70.07  -70.71
             STACK1   -69.21  -65.60  -60.00  -65.60  -69.21  -70.71
             STACK1   -70.07  -67.29  -62.48  -55.76  -47.35  -37.50
             STACK1   -35.19  -31.82  -27.48  -22.30  -16.44  -10.09
             STACK1    -3.43    3.34   10.00    3.34   -3.43  -10.09
             STACK1   -16.44  -22.30  -27.48  -31.82  -35.19  -37.50
SO YBADJ     STACK1    34.47   32.89   30.31   26.81   22.50   17.50
             STACK1    11.97    6.08    0.00   -6.08  -11.97  -17.50
             STACK1   -22.50  -26.81  -30.31  -32.89  -34.47  -35.00
             STACK1   -34.47  -32.89  -30.31  -26.81  -22.50  -17.50
             STACK1   -11.97   -6.08    0.00    6.08   11.97   17.50
             STACK1    22.50   26.81   30.31   32.89   34.47   35.00
SRCGROUP  ALL
SO FINISHED

RE STARTING
   GRIDPOLR POL1 STA
   GRIDPOLR POL1 ORIG STACK1
   GRIDPOLR POL1 DIST 175. 350. 500. 1000.
   GRIDPOLR POL1 GDIR 36 10 10
   GRIDPOLR POL1 END
RE FINISHED

ME STARTING
   SURFFILE  AERMET2.SFC
   PROFFILE  AERMET2.PFL
   SURFDATA  14735  1988  ALBANY,NY
   UAIRDATA  14735  1988  ALBANY,NY
   SITEDATA  99999  1988  HUDSON
   PROFBASE  0.0  METERS
ME FINISHED

OU STARTING
   RECTABLE  ALLAVE  FIRST  SECOND
   MAXTABLE  ALLAVE  50
OU FINISHED
```

FIGURE 2-2. EXAMPLE INPUT RUNSTREAM FILE FOR SAMPLE PROBLEM

2.4.7 Using the Error Message File to Debug the Input Runstream File

The previous sections in this tutorial have lead through the step-by-step construction of a sample runstream input file for AERMOD. This simple example problem illustrated the usage of the most commonly used options of the AERMOD model. However, many real-time applications of the model will be much more complex than this example, perhaps involving multiple sources and source groups, multiple receptor networks, the addition of discrete receptor locations, and/or elevated terrain heights. Since humans are prone to make errors from time to time, an effort has been made to develop detailed error handling capabilities for the AERMOD model.

The error handling capabilities of the AERMOD model are designed to accomplish two things for the user. First, the model should read through the complete input file and report all occurrences of errors or suspect entries before stopping, rather than stopping on the first instance (and every instance thereafter) of an error in the input file. Second, the model should provide error and warning messages that are detailed and descriptive enough that they will help the user in his/her effort to debug the input file. The remainder of this section provides of brief introduction to the use of the model's error handling capabilities. Appendix C of this volume provides more details about the error handling provided by the AERMOD model, including a listing and explanation of all error and other types of messages generated by the model.

The AERMOD model generates messages during the processing of the input data and during the execution of model calculations. These messages inform the user about a range of possible conditions including:

- Errors that will halt any further processing, except to identify additional error conditions;
- Warnings that do not halt processing but indicate possible errors or suspect conditions; and

- Informational messages that may be of interest to the user but have no direct bearing on the validity of the results.

As the model encounters a condition for which a message is generated, the model writes the message to a temporary storage file. At the completion of the setup processing for a run, and at the completion of the model calculations, the model rereads the message file and generates a summary of the messages which is included in the main printed output file. If the processing of the model setup information indicates no errors or warnings, and the user has selected the option to RUN the model calculations on the CO RUNORNOT card, then the model will simply write a statement to the print file that the model setup was completed successfully. Otherwise, the model will report a summary of the messages encountered. The summary of model setup messages that would be generated for the example problem if the option NOT to run was chosen is shown in Figure 2-3. This summary table reports the total number of occurrences for each of the message types, and lists the detailed message for any fatal errors or warning messages that were generated. In this case, since there were no errors or suspicious conditions in the setup file, there are no error or warning messages listed.

An example of the warning message that would have been generated had we left out the card on the RE pathway that specifies the origin of the polar receptor network is shown below:

```
RE W220 39 REPOLR: Missing Origin (Use Default = 0,0) In GRIDPOLR      POL1
|   |   |    |         |                                                 |
|   |   |    |         |                                                 |
|   |   |    |         |                                               Hints
|   |   |    |         |
|   |   |    |       Detailed error/warning message
|   |   |    |
|   |   |  Subroutine from which message is generated
|   |   |
|   |  Line number of file where message occurred
|   |
|  Message code - including message type (E, W, I) and message number
|
Pathway ID where message originated
```

Since this is a warning message, it would have appeared at the end of the message summary table in the output file, but it would not have halted processing of the data. The last item on the message line, "Hints," may include such information as the keyword or parameter name causing the error, the source ID, group ID or (as in this case) the network ID involved, or perhaps the date variable identifying when the message occurred during the processing of the meteorological data, such as an informational message identifying the occurrence of a calm wind.

For new users and for particularly complex applications, it is strongly recommended that the model first be run with the RUNORNOT keyword (on the CO pathway) set NOT to run. In this way, the user can determine if the model is being setup properly by the runstream file before committing the resources to perform a complete run. The user should make a point of examining any warning messages carefully to be sure that the model is operating as expected for their application, since these messages will not halt processing by the model. In most cases, the detailed messages will provide enough information for the user to determine the location and nature of any errors in the runstream setup file. If the intent of the message is not immediately clear, then the user should refer to the more detailed descriptions provided in Appendix C for the particular error code generated.

In deciphering the error and warning messages, the line number provided as part of the message may be particularly helpful in locating the error within the input file. However, if it is an error of omission that is caught by the error checking performed at the completion of inputs for a pathway, then the line number will correspond to the last record for that pathway. The user may need to examine all of the messages carefully before locating the error or errors, especially since a single occurrence of certain types of errors may lead to other error conditions being identified later in the input file which do not really constitute errors in themselves. An example of this is provided in Figure 2-4, which shows some inputs for the SO pathway where the building dimension keywords have been typed incorrectly, and the associated list of error messages. Since continuation cards were being used for the building width inputs, and the keyword was entered incorrectly on the first line, the subsequent records

were also taken by the model to be invalid keyword inputs. While the error messages are the same for these records, the message originates from a different part of the model (SUBROUTINE SOCARD) for the records with the blank keyword.

Since the detailed error and warning messages are listed in the output file as part of the message summary table, there will generally not be a need for the user to examine the contents of the detailed message file. For this reason, the default operation of the model is to write the messages that are generated by a particular run to a temporary file that is deleted when the run is completed. If the user wishes to examine the complete list of detailed messages (of all types), there is an optional keyword available on the CO pathway for that purpose. The ERRORFIL keyword, which is described in detail in Section 3.2.7, allows the user to save the complete list of detailed messages to a user-specified filename.

```
  *** Message Summary For AERMOD Model Setup ***


  --------- Summary of Total Messages ---------

A Total of           0 Fatal Error Message(s)
A Total of           0 Warning Message(s)
A Total of           0 Information Message(s)


   ******** FATAL ERROR MESSAGES ********
               ***  NONE  ***


   ********   WARNING MESSAGES   ********
               ***  NONE  ***


   ************************************
   *** SETUP Finishes Successfully ***
   ************************************
```

FIGURE 2-3. EXAMPLE MESSAGE SUMMARY TABLE FOR RUNSTREAM SETUP

```
SO STARTING
   LOCATION  STACK1  POINT  0.0   0.0   0.0
** Point Source       QS    HS    TS     VS   DS
** Parameters:       ----  ----  ----   ----  ---
   SRCPARAM  STACK1  500.0 65.0 425.0   15.0  5.0
   BUILDHTS  STACK1  36*50.
   BUILDWTS  STACK1    62.26   72.64   80.80   86.51   89.59   89.95
             STACK1    87.58   82.54   75.00   82.54   87.58   89.95
             STACK1    89.59   86.51   80.80   72.64   62.26   50.00
             STACK1    62.26   72.64   80.80   86.51   89.59   89.95
             STACK1    87.58   82.54   75.00   82.54   87.58   89.95
             STACK1    89.59   86.51   80.80   72.64   62.26   50.00
   XBADJ     STACK1   -47.35  -55.76  -62.48  -67.29  -70.07  -70.71
             STACK1   -69.21  -65.60  -60.00  -65.60  -69.21  -70.71
             STACK1   -70.07  -67.29  -62.48  -55.76  -47.35  -37.50
             STACK1   -35.19  -31.82  -27.48  -22.30  -16.44  -10.09
             STACK1    -3.43    3.34   10.00    3.34   -3.43  -10.09
             STACK1   -16.44  -22.30  -27.48  -31.82  -35.19  -37.50
   YBADJ     STACK1    34.47   32.89   30.31   26.81   22.50   17.50
             STACK1    11.97    6.08    0.00   -6.08  -11.97  -17.50
             STACK1   -22.50  -26.81  -30.31  -32.89  -34.47  -35.00
             STACK1   -34.47  -32.89  -30.31  -26.81  -22.50  -17.50
             STACK1   -11.97   -6.08    0.00    6.08   11.97   17.50
             STACK1    22.50   26.81   30.31   32.89   34.47   35.00
   SRCGROUP  ALL
SO FINISHED
```

```
 *** Message Summary For AERMOD Model Setup ***
 --------- Summary of Total Messages ---------
A Total of           6 Fatal Error Message(s)
A Total of           0 Warning Message(s)
A Total of           0 Information Message(s)

   ******** FATAL ERROR MESSAGES ********
SO E105   17 EXKEY : Invalid Keyword Specified. The Troubled Keyword is BUILDHTS
SO E105   18 EXKEY : Invalid Keyword Specified. The Troubled Keyword is BUILDWTS
SO E105   19 SOCARD: Invalid Keyword Specified. The Troubled Keyword is BUILDWTS
SO E105   20 SOCARD: Invalid Keyword Specified. The Troubled Keyword is BUILDWTS
SO E105   21 SOCARD: Invalid Keyword Specified. The Troubled Keyword is BUILDWTS
...

   ********   WARNING MESSAGES   ********
              ***  NONE  ***

   ****************************************
   *** SETUP Finishes UN-successfully ***
   ****************************************
```

FIGURE 2-4. EXAMPLE OF KEYWORD ERROR AND ASSOCIATED MESSAGE SUMMARY TABLE

2.4.8 Running the Model and Reviewing the Results

Now that we have a complete and error-free runstream input file, we are ready to run the model and then review the results. The PC-executable file available on the SCRAM website opens the runstream input and printed output files explicitly within the model using internally specified filenames of AERMOD.INP and AERMOD.OUT, respectively. The model can be executed from the command prompt by simply typing the name AERMOD, as follows:

```
C:\>AERMOD
```

The "c-prompt" of DOS has been represented by the characters "C:\>", but may appear different on different machines. The important points are that the AERMOD.EXE file either be in the directory from which you are attempting to run the model, or in a directory that is included on the DOS PATH command when the system is "booted-up." The runstream input file (AERMOD.INP) must also be located in the directory from which the model is being executed. The model can also be executed by double clicking on the executable file from Windows Explorer.

As mentioned above, the SCRAM PC-executable file for AERMOD opens the input and output files explicitly. One reason for this is to allow for the model to write an update on the status of processing to the PC terminal screen. For the AERMOD model, the model first indicates that setup information is being processed and then gives the Julian day currently being processed. If no status message is seen then the model did not load into memory properly. If the model stops after completing the setup processing, then either the RUNORNOT option was set NOT to run. If a fatal error is encountered during the setup processing, then a message to that effect will be written to the screen and model execution will be stopped. Another reason for not sending the printed output to the default output device (i.e., to the screen or redirected to a file), is so that any DOS error messages will be visible on the screen and not be written to the printed file. One such message might be that

there is insufficient memory available to run the program. Handling of DOS error messages may require some knowledge of DOS, unless the meaning of the message is obvious.

The order of contents and organization of the main output file for the AERMOD model is presented in Figure 2-5.

Echo of Input Runstream Images

Summary of Runstream Setup Messages

Summary of Inputs
- Summary of Modeling Options
- Summary of Source Data
- Summary of Receptor Data
- Summary of Meteorology Data

Model Results

- Daily Results for Each Averaging Period Selected for Each Day Processed (If Applicable)
  - DAYTABLE Keyword
- PERIOD Results for Each Source Group (If Applicable)
  - PERIOD Parameter on AVERTIME Keyword
- Short Term Average Results (High, Second High, etc.) by Receptor for Each Source Group (If Applicable)
  - RECTABLE Keyword
- Overall Maximum Short Term Average Results for Each Source Group (If Applicable)
  - MAXTABLE Keyword

Summary Tables of High Values for Each Averaging Period and Source Group (Always provided if PERIOD averages or the RECTABLE keyword are used)

Summary of Complete Model Execution Messages

FIGURE 2-5. ORGANIZATION OF AERMOD MODEL OUTPUT FILE

Each page of the output file, except for the echo of the input file images, is labeled with the model name and version number, user-specified title(s), page number, and, for the PC version of the model, the date and time of the particular run. Also included as part of the header information for each page is a one-line summary of the modeling options used for that particular run. The modeling options are listed as the secondary keywords used to control the options, such as DFAULT, CONC, etc. (Details about the date/time routines and other PC-specific features of the computer code are discussed in Section 4.0.)

Since the complete input file is normally echoed back as part of the output file, and since processing of the inputs stops when the OU FINISHED card is reached, the run can be duplicated by simply specifying the output filename as the input runstream file. Alternatively, the input records could be "cut and pasted" from the output file to a separate file using a text editor.

By default, the model will echo each line of the input runstream file to the printed output file. This provides a convenient record of the inputs as originally read into the model, without any rounding of numerical values that may appear in the input summary tables. As noted above, it also means that the output file can be used as an input file to the model to reproduce a particular application. However, for some applications, the length of the input runstream file may be too cumbersome to include the entire set of inputs at the beginning of each output file. This may happen, for example, if a large number of sources are being defined or if a large number of discrete receptor locations are used. For this reason, the user is provided with the option to "turn off" the echoing of the input file at any point within the runstream file. This is accomplished by entering the keywords "NO ECHO" in the first two fields anywhere within the runstream file. In other words, place NO in the pathway field, followed by a space and then ECHO. None of the input runstream images after the NO ECHO will be echoed to the output file. Thus, a user may choose to place NO ECHO after the Control pathway in order to keep the control options echoed, but suppress echoing the rest of the input file.

The details of the message summary tables were discussed in the previous section. A portion of the summary of modeling option inputs is shown in Figure 2-6 for the simple example described in this section. The summary of source parameter input data includes separate tables for each source type, rather than combining all sources onto a single table. In this way the column headings are specific to the source type.

Figure 2-7 presents an example of the results output for the second highest values by receptor for our sample problem. These values are the second highest 3-hour averages at each receptor location. The number in parentheses following each concentration value is the date corresponding to each value. The date is given as an eight digit integer variable that includes the year (2-digits), month, day, and hour corresponding to the end of the averaging period.

For each of the different types of model result tables, the controlling keyword is identified in Figure 2-5 at the end of the description. All of the outputs of the same type, e.g. high values by receptor, are printed together, and the order of tables loops through all source groups for a particular averaging period, and then loops through all averaging periods. The summary tables of high values at the end of the model results follow the same order of loops. An example of the summary tables for our sample problem is shown in Figure 2-8. The summaries for all averaging periods have been combined onto a single figure, but would appear on separate pages of the actual output file.

```
 *** AERMOD - VERSION 04209 ***    *** A Simple Example Problem for the AERMOD Model with PRIME            ***        09/13/04
                                   ***                                                                     ***        15:40:59
**MODELOPTs:                                                                                                          PAGE   1
CONC                               FLAT

                                          ***     MODEL SETUP OPTIONS SUMMARY       ***
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

**Model Is Setup For Calculation of Average CONCentration Values.

  --  DEPOSITION LOGIC  --
**Model Uses NO DRY DEPLETION.  DDPLETE =  F
**Model Uses NO WET DEPLETION.  WDPLETE =  F
**NO GAS DRY DEPOSITION Data Provided.

**Model Uses RURAL Dispersion Only.

**Model Uses User-Specified Options:
        1. Stack-tip Downwash.
        2. Model Assumes Receptors on FLAT Terrain.

**Model Assumes No FLAGPOLE Receptor Heights.

**Model Calculates  2 Short Term Average(s) of:   3-HR  24-HR
    and Calculates PERIOD Averages

**This Run Includes:     1 Source(s);      1 Source Group(s); and     144 Receptor(s)

**The Model Assumes A Pollutant Type of:  SO2

**Model Set To Continue RUNning After the Setup Testing.

**Output Options Selected:
         Model Outputs Tables of PERIOD Averages by Receptor
         Model Outputs Tables of Highest Short Term Values by Receptor (RECTABLE Keyword)
         Model Outputs Tables of Overall Maximum Short Term Values (MAXTABLE Keyword)

**NOTE:  The Following Flags May Appear Following CONC Values:  c for Calm Hours
                                                                m for Missing Hours
                                                                b for Both Calm and Missing Hours

**Misc. Inputs:  Base Elev. for Pot. Temp. Profile (m MSL) =     0.00 ;  Decay Coef. =    0.000     ;  Rot. Angle =     0.0
                 Emission Units = GRAMS/SEC                                ;  Emission Rate Unit Factor =   0.10000E+07
                 Output Units   = MICROGRAMS/M**3

**Approximate Storage Requirements of Model =     1.2 MB of RAM.
```

FIGURE 2-6. SAMPLE OF MODEL OPTION SUMMARY TABLE FROM AN AERMOD MODEL OUTPUT FILE

```
*** AERMOD - VERSION 04209 ***    *** A Simple Example Problem for the AERMOD Model with PRIME            ***        09/13/04
                                   ***                                                                    ***        15:40:59
**MODELOPTs:                                                                                                          PAGE  10
CONC                               FLAT
                             *** THE   2ND HIGHEST  3-HR AVERAGE CONCENTRATION   VALUES FOR SOURCE GROUP:  ALL      ***
                                 INCLUDING SOURCE(S):      STACK1  ,
                                  *** NETWORK ID: POL1     ;  NETWORK TYPE: GRIDPOLR ***
                                      ** CONC OF SO2      IN MICROGRAMS/M**3                          **
DIRECTION |                                                DISTANCE (METERS)
(DEGREES) |          175.00                 350.00                 500.00                 1000.00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
     10.0 |       0.76158 (88030321)      1.92853 (88030115)      3.31346 (88030115)      5.22765 (88030218)
     20.0 |       0.63637 (88030212)      1.92844 (88030115)      5.85553 (88030218)     16.97758 (88030218)
     30.0 |       0.62623 (88030212)      1.92797 (88030115)      5.83875 (88030218)     16.92332 (88030218)
     40.0 |       0.62622 (88030212)      1.92504 (88030115)      3.31345 (88030115)      4.79368 (88030218)
     50.0 |       0.62622 (88030212)      1.53776 (88030112)      2.70655 (88030112)      2.97378 (88030321)
     60.0 |       0.62622 (88030212)      1.60102 (88030321)      2.70653 (88030112)      3.29819 (88030321)
     70.0 |       0.62622 (88030212)      2.38433 (88030312)      3.14235 (88030312)      2.97029 (88030312)
     80.0 |       1.22236 (88030321)      5.70971 (88030312)      7.70416 (88030312)      7.52613 (88030312)
     90.0 |       5.42790 (88030112)     14.05461 (88030312)     19.21173 (88030312)     18.62586 (88030312)
    100.0 |      10.56986 (88030115)     68.04736 (88030112)     69.01392 (88030112)     48.93560 (88030112)
    110.0 |      13.40298 (88030115)    240.77687 (88030112)    261.00546 (88030112)    155.58842 (88030112)
    120.0 |      11.83663 (88030115)    199.43596 (88030115)    266.38513 (88030115)    154.97153 (88030115)
    130.0 |       7.82604 (88030115)    118.05672 (88030115)    151.17198 (88030115)    100.53476 (88030115)
    140.0 |       3.76063 (88030312)     55.34053 (88030115)     71.91618 (88030115)     36.71769 (88030115)
    150.0 |       1.38547 (88030209)     15.82063 (88030115)     18.09701 (88030115)     13.81106 (88030312)
    160.0 |       0.62622 (88030212)      2.88999 (88030115)      4.68343 (88030115)      4.83882 (88030115)
    170.0 |       0.62622 (88030212)      1.83427 (88030115)      3.66103 (88030112)      3.55293 (88030112)
    180.0 |       0.69932 (88030321)      1.89684 (88030115)      3.31302 (88030115)      3.21311 (88030115)
    190.0 |       0.62622 (88030212)      1.53751 (88030112)      2.97770 (88030415)      3.21308 (88030115)
    200.0 |       0.62622 (88030212)      1.53790 (88030112)      2.70655 (88030112)      3.21308 (88030115)
    210.0 |       0.62622 (88030212)      1.53802 (88030112)      2.70655 (88030112)      2.60891 (88030112)
    220.0 |       0.62622 (88030212)      1.53802 (88030112)      2.70655 (88030112)      2.60891 (88030112)
    230.0 |       0.62095 (88030321)      1.53802 (88030112)      2.70655 (88030112)      2.60891 (88030112)
    240.0 |       0.52274 (88030321)      1.53802 (88030112)      2.70655 (88030112)      2.60891 (88030112)
    250.0 |       0.42210 (88030321)      1.53802 (88030112)      2.70655 (88030112)      2.60891 (88030112)
    260.0 |       0.35358 (88030209)      1.92853 (88030115)      2.70655 (88030112)      2.95926 (88030212)
    270.0 |       0.32961 (88030209)      1.92853 (88030115)      3.31346 (88030115)      3.21308 (88030115)
    280.0 |       0.30712 (88030209)      1.92853 (88030115)      3.31346 (88030115)      3.21308 (88030115)
    290.0 |       0.30434 (88030321)      1.92853 (88030115)      3.31345 (88030115)      3.21308 (88030115)
    300.0 |       0.30434 (88030321)      1.92853 (88030115)      3.31346 (88030115)      3.21308 (88030115)
    310.0 |       0.30434 (88030321)      1.92853 (88030115)      3.31346 (88030115)      3.21308 (88030115)
    320.0 |       0.30434 (88030321)      1.92853 (88030115)      3.31346 (88030115)      3.21308 (88030115)
    330.0 |       0.30434 (88030321)      1.92853 (88030115)      3.31345 (88030115)      3.21308 (88030115)
    340.0 |       0.30464 (88030306)      1.92853 (88030115)      3.31346 (88030115)      3.21308 (88030115)
    350.0 |       0.37996 (88030306)      1.92853 (88030115)      2.70655 (88030112)      2.70615 (88030215)
    360.0 |       0.52542 (88030321)      1.68995 (88030215)      3.04580 (88030215)      3.21308 (88030115)
```

FIGURE 2-7. EXAMPLE OUTPUT TABLE OF HIGH VALUES BY RECEPTOR

```
  *** AERMOD - VERSION 04209 ***    *** A Simple Example Problem for the AERMOD Model with PRIME            ***        09/13/04
                                   ***                                                                    ***       15:40:59
**MODELOPTs:                                                                                                          PAGE  15
CONC                               FLAT

                                          *** THE SUMMARY OF MAXIMUM PERIOD (    96 HRS) RESULTS ***


                                      ** CONC OF SO2      IN MICROGRAMS/M**3                          **

                                                                                                  NETWORK
GROUP ID                      AVERAGE CONC               RECEPTOR  (XR, YR, ZELEV, ZHILL, ZFLAG)   OF TYPE  GRID-ID
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

ALL      1ST HIGHEST VALUE IS      25.68469 AT (     433.01,     -250.00,      0.00,      0.00,      0.00)  GP   POL1
         2ND HIGHEST VALUE IS      24.36184 AT (     469.85,     -171.01,      0.00,      0.00,      0.00)  GP   POL1


*** AERMOD -                                                  *** THE SUMMARY OF HIGHEST  3-HR RESULTS ***

                                      ** CONC OF SO2      IN MICROGRAMS/M**3                          **

                                                   DATE                                                          NETWORK
GROUP ID                      AVERAGE CONC     (YYMMDDHH)            RECEPTOR  (XR, YR, ZELEV, ZHILL, ZFLAG)     OF TYPE  GRID-ID
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

ALL      HIGH  1ST HIGH VALUE IS     335.58878  ON 88030112: AT (     433.01,     -250.00,      0.00,      0.00,      0.00)  GP   POL1

         HIGH  2ND HIGH VALUE IS     266.38513  ON 88030115: AT (     433.01,     -250.00,      0.00,      0.00,      0.00)  GP   POL1


                                            *** THE SUMMARY OF HIGHEST 24-HR RESULTS ***

                                      ** CONC OF SO2      IN MICROGRAMS/M**3                          **

                                                   DATE                                                          NETWORK
GROUP ID                      AVERAGE CONC     (YYMMDDHH)            RECEPTOR  (XR, YR, ZELEV, ZHILL, ZFLAG)     OF TYPE  GRID-ID
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

ALL      HIGH  1ST HIGH VALUE IS      91.45594  ON 88030124: AT (     433.01,     -250.00,      0.00,      0.00,      0.00)  GP   POL1

         HIGH  2ND HIGH VALUE IS      11.35450  ON 88030324: AT (     866.03,     -500.00,      0.00,      0.00,      0.00)  GP   POL1

 *** RECEPTOR TYPES:  GC = GRIDCART
                      GP = GRIDPOLR
                      DC = DISCCART
                      DP = DISCPOLR
```

FIGURE 2-8. EXAMPLE OF RESULT SUMMARY TABLES FOR THE AERMOD MODEL

2.5 MODIFYING AN EXISTING RUNSTREAM FILE

As noted earlier, one of the advantages of the keyword/parameter approach and the flexible format adopted for the input runstream file is that it will be easier for the user to make modifications to the runstream file and obtain the desired result. This section briefly illustrates some examples of how a runstream file can be modified. It is assumed that the reader is familiar with the operation of and basic editing commands for a text editor (i.e., a program that edits ASCII files), and is familiar with the previous sections of this tutorial.

2.5.1 Modifying Modeling Options

Depending on the type of analysis being performed, the user may need to modify the modeling options and run the model again. Because of the descriptive nature of the keywords and the secondary keywords used to control the modeling options, this can easily be done with the new runstream file, and usually without having to refer back to the user's guide each time a modification is attempted.

2.5.2 Adding or Modifying a Source or Source Group

Modifying the input file to add a source or a source group, or to add a source to a source group, is as simple as just adding it. There is no need to specify the total number of sources in the run, which would then have to be changed if more sources were added. The same applies to the number of groups, or the number of sources per group. If the user attempts to input more than the total number of sources or groups allowed for a particular run, an error message will be generated to that effect. Also, modifying a source group to delete a source is as easy as just deleting it from the input card, without having to change any other inputs.

Another way of "deleting" a source or a group from an input file is to place a "**" in the pathway field of the card or cards which define the source or group to "comment out" those inputs. This approach, which was discussed above in Section 2.1.2, has the advantage of leaving the input data for the source or group in the input file for possible later use. It doesn't matter

whether the "**" is entered with the text editor in "insert" mode, in which case the other inputs of that line are moved over, or if it is in "overtype" mode, which would replace the pathway ID that was already there.

2.5.3 Adding or Modifying a Receptor Network

As with source data, adding to or modifying the receptor information in the AERMOD model is relatively straight forward. The problem of having to make several changes to accomplish one small modification, such as adding a distance to a polar receptor network, has been avoided in the new model. All that the user needs to do is to add the new distance on the appropriate input card, which is easily identifiable because of the use of descriptive keywords. The model checks to ensure that the user does not attempt to specify more than the maximum number of receptors for a particular run, and generates an appropriate message if too many are input.

2.5.4 Modifying Output Options

Modifying the output options involves many of the same principles that are described above. In addition, all of the output options are structured in a way that allows the user to select options for specific averaging periods, so that the user may find it useful to copy a record or group of records set up for one averaging period and simply change the averaging period parameter. The other important short cut that is available for the printed table output options is to use the secondary keyword ALLAVE to indicate that the option applies to all averaging periods that are calculated. In this way, there will be no need to change the output options if a new averaging period is added to a run or if one is deleted.

3.0 DETAILED KEYWORD REFERENCE

This section of the AERMOD User's Guide provides a detailed reference for all of the input keyword options for the AERMOD model. The information provided in this section is more complete and detailed than the information provided in the Brief Tutorial in Section 2. Since this section is intended to meet the needs of experienced modelers who may need to understand completely how particular options are implemented in the model, the information for each keyword should stand on its own. This section assumes that the reader has a basic understanding of the keyword/parameter approach used by the model for specification of input options and data. Novice users should first review the contents of Section 2 in order to obtain that understanding.

3.1 OVERVIEW

The information in this section is organized by function, i.e., the keywords are grouped by pathway, and are in a logical order based on their function within the model. The order of keywords presented here is the same as the order used in the functional keyword reference in Appendix B, and the Quick Reference section at the end of the volume. The syntax for each keyword is provided, and the keyword type is specified - either mandatory or optional and either repeatable or non-repeatable. Unless noted otherwise, there are no special requirements for the order of keywords within each pathway, although the order in which the keywords are presented here and in Appendix B is recommended. Any keyword which has special requirements for its order within the pathway is so noted following the syntax and type description.

The syntax descriptions in the following sections use certain conventions. Parameters that are in all capital letters and underlined in the syntax description are secondary keywords that are to be entered as indicated for that keyword. Other parameters are given descriptive names to convey the meaning of the parameter, and are listed with an initial capital letter. Many of the parameter names used correspond to variable names used in the computer code of the model. Parentheses around a parameter indicate that the parameter is optional for that keyword. The default that is taken when an optional parameter is left blank is explained in the discussion for that keyword.

3.2 CONTROL PATHWAY INPUTS AND OPTIONS

The **CO**ntrol pathway contains the keywords that provide the overall control of the model run. These include the dispersion options, averaging time options, terrain height options, and others that are described below. The CO pathway must be the first pathway in the runstream input file.

3.2.1 Title Information

There are two keywords that allow the user to specify up to two lines of title information that will appear on each page of the main output file from the model. The first keyword, TITLEONE, is mandatory, while the second keyword, TITLETWO, is optional. The syntax and type for the keywords are summarized below:

Syntax:	`CO TITLEONE Title1` `CO TITLETWO Title2`
Type:	`TITLEONE - Mandatory, Non-repeatable` `TITLETWO - Optional, Non-repeatable`

The parameters Title1 and Title2 are character parameters of length 68, which are read as a single field from columns 13 to 80 of the input record. The title information is taken as it appears in the runstream file without any conversion of lower case to upper case letters. If the TITLETWO keyword is not included in the runstream file, then the second line of the title in the output file will appear blank.

3.2.2 Dispersion Options

The dispersion options are controlled by the MODELOPT keyword on the CO pathway. The syntax, type, and order of the MODELOPT keyword are summarized below:

Syntax:	`CO MODELOPT` <u>`DFAULT`</u> <u>`CONC`</u> <u>`FLAT`</u> <u>`NOSTD`</u> <u>`NOCHKD`</u> <u>`NOWARN`</u> <u>`SCREEN`</u> <u>`TOXICS`</u> <u>`SCIM`</u>
Type:	`Mandatory, Non-repeatable`

where the secondary keyword parameters are described below (the order and spacing of these parameters is not critical):

DFAULT - Specifies that the regulatory default options will be used;

CONC - Specifies that concentration values will be calculated (note that deposition algorithms have not been implemented in AERMOD yet);

FLAT - Specifies that the non-default option of assuming flat terrain will be used;

NOSTD - Specifies that the non-default option of no stack-tip downwash will be used;

NOCHKD - Specifies that the non-default option of suspending date checking will be used for non-sequential meteorological data files;

NOWARN - Specifies that the option of suppressing the detailed listing of warning messages in the main output file will be used (the number of warning messages is still reported, and warning messages are still included in the error file controlled by the CO ERRORFIL card described in Section 3.2.14);

SCREEN - Specifies that the non-default option for running AERMOD in a screening mode will be used;

TOXICS - Specifies use of air toxics option(s), including SCIM and area source optimizations; and

SCIM - Sampled Chronological Input Model - used only with the ANNUAL average option to reduce runtime by sampling meteorology at a user-specified regular interval; SCIM sampling parameters must be specified on the ME pathway.

The regulatory default option in AERMOD includes the use of stack-tip downwash, incorporates the effects of elevated terrain, and includes the calms and missing data processing routines. The regulatory default option in AERMOD also forces the use of a 4-hour half life when modeling SO_2 in an urban source, and does not allow for exponential decay for other applications.

The missing data processing routines that are included in the AERMOD model allow the model to handle missing meteorological data in the processing of short term averages. The model

treats missing meteorological data in the same way as the calms processing routine, i.e., it sets the concentration values to zero for that hour, and calculates the short term averages according to EPA's calms policy, as set forth in the Guideline. Calms and missing values are tracked separately for the purpose of flagging the short term averages. An average that includes a calm hour is flagged with a 'c', an average that includes a missing hour is flagged with an 'm', and an average that includes both calm and missing hours is flagged with a 'b'. If the number of hours of missing meteorological data exceeds 10 percent of the total number of hours for a given model run, a cautionary message is written to the main output file, and the user is referred to Section 5.3.2 of "Meteorological Monitoring Guidance for Regulatory Modeling Applications" (EPA, 2004).

The screening mode of AERMOD, which is controlled by the SCREEN keyword on the MODELOPT card, forces the model calculations to represent values for the plume centerline, regardless of the source-receptor-wind direction orientation. This option is included in AERMOD to facilitate the use of the model with a Windows-based AERMOD Screening Model interface (not yet developed) to estimate worst case impacts. Its use outside of that context is not recommended. Since the screening model is designed to be used with a non-sequential meteorological data file, representing a matrix of conditions, the SCREEN option also forces the use of the NOCHKD option described above, even if NOCHKD is not included on the MODELOPT card. The SCREEN option also restricts the averaging period options to 1-hour averages only on the AVERTIME card (see Section 3.2.3).

The AERMOD model includes the Sampled Chronological Input Model (SCIM) option for air toxics applications. In order to utilize this option, the user must include the TOXICS and SCIM keywords together on the CO MODELOPT card. Since the TOXICS option is a non-regulatory default option, the DFAULT keyword should not be included on the MODELOPT card. If the DFAULT keyword is present on the MODELOPT card, the DFAULT option will override the TOXICS option if it is present, and any other enhancements dependent on the TOXICS option. The SCIM approach associated with the TOXICS option is described below.

When the TOXICS option is specified, the area source integration routine is optimized to reduce model runtime. This is accomplished by incorporation of a three-tiered approach using the Romberg numerical integration, a 2-point Gaussian Quadrature routine for numerical integration, or a point source approximation based on the location of the receptor relative to the source. In the regulatory default mode the Romberg numerical integration is utilized for all receptors.

If the non-default TOXICS option is specified, the user may also use the SCIM option to reduce model runtime. The SCIM option can only be used with the ANNUAL average option, and is primarily applicable to multi-year model simulations. The approach used by the SCIM option is to sample the meteorological data at a user-specified regular interval to approximate the long-term (i.e., ANNUAL) average impacts. Studies have shown that the uncertainty in modeled results introduced by use of the SCIM option is generally lower for area sources than for point sources.

When only the regular sampling is selected, hourly concentrations are calculated in the normal fashion for each sampled hour. The annual average concentration is then simply calculated by dividing the cumulative concentration for the sampled hours by the number of hours sampled (arithmetic average), i.e.,

$$C = \sum C_S \ / \ N_S$$

where:

C = Calculated concentration

$\sum C_S$ = Cumulatibe impacts for the sampled hours

N_S = Number of sampled hours

To use the SCIM option, the user must include the SCIM and TOXICS keywords on the CO MODELOPT card, and also specify the SCIM sampling parameters on the ME SCIMBYHR card. The format and syntax of the ME SCIMBYHR keyword are described in Section 3.5.7.

3.2.3 Averaging Time Options

The averaging periods for AERMOD are selected using the AVERTIME keyword. The syntax and type of the AVERTIME keyword are summarized below:

Syntax:	`CO AVERTIME  Time1  Time2  Time3  Time4  MONTH  PERIOD`
Type:	`Mandatory, Non-repeatable`

where the parameters Time1 . . . Time4 refer to the user-specified short term averaging periods of 1, 2, 3, 4, 6, 8, 12, or 24 hours, the secondary keyword MONTH refers to monthly averages (for calendar months), and the secondary keyword PERIOD refers to the average for the entire data period. Any of the short term averaging periods listed above may be selected for a given run, as long as the total data storage needed by the model does not exceed the available computer memory. Since the monthly averages are treated as short term averages, the user can select appropriate output options, such as the second highest values by receptor, on the OUtput pathway.

The location of the PERIOD keyword in the parameter list is not critical. The order of the short term averaging periods (including MONTH) is also not critical, although it does control the order of the averaging period result tables in the main output file. Generally, it is recommended that the short term averaging periods be input in increasing order, unless there is a clear advantage in doing otherwise.

3.2.4 Urban Modeling Option

The AERMOD model allows the user to incorporate the effects of increased surface heating from an urban area on pollutant dispersion under stable atmospheric conditions. The user defines the input parameters for the urban area with the URBANOPT keyword on the CO pathway, and then identifies which sources are to be modeled with urban effects using the URBANSRC keyword on the SO pathway (see Section 3.3.4). The syntax and type of the URBANOPT keyword are summarized below:

Syntax:	`CO URBANOPT  UrbPop  (UrbName)  (UrbRoughness)`
Type:	`Optional, Non-repeatable`

where the UrbPop parameter specifies the population of the urban area, the optional UrbName parameter may be used to identify the name of the urban area, and the optional UrbRoughness

parameter may be used to specify the urban surface roughness length. Note the UrbName must be specified if the user wants to specify the urban roughness length. A default value of 1.0 meter will be used for the urban roughness length if the UrbRoughness parameter is omitted.

3.2.5 Specifying the Pollutant Type

The POLLUTID keyword is used to identify the type of pollutant being modeled for a particular run. The syntax, type, and order of the POLLUTID keyword are summarized below:

Syntax:	`CO POLLUTID  Pollut`
Type:	`Mandatory, Non-repeatable`

where the Pollut parameter may be name of up to eight characters. Examples include SO2, NOX, CO, PM10, TSP, and OTHER. The only choice that currently has any impact on the results is the selection of PM10 (or PM-10) with the multi-year option for generating the high-sixth-high in five years. Otherwise, the pollutant ID currently has no effect on the calculations made in AERMOD.

3.2.6 Modeling With Exponential Decay

The model provides the option to use exponential decay of the pollutant being modeled. Two keywords are available for this purpose, the HALFLIFE and DCAYCOEF keywords. The syntax, type, and order of these keywords are summarized below:

Syntax:	`CO HALFLIFE  Haflif` `CO DCAYCOEF  Decay`
Type:	`Optional, Non-repeatable`

where the Haflif parameter is used to specify the half life for exponential decay in seconds, and the parameter Decay is used to specify the decay coefficient in units of s^{-1}. The relationship between these parameters is DECAY = 0.693/HAFLIF.

Only one of these keywords may be specified in a given run. If more than one is encountered, a non-fatal warning message is generated and the first specification is used in the modeling.

3.2.7 Flagpole Receptor Height Option

The FLAGPOLE keyword specifies that receptor heights above local ground level (i.e. flagpole receptors) are allowed on the REceptor pathway. The FLAGPOLE keyword may also be used to specify a default flagpole receptor height other than 0.0 meters. The syntax and type of the FLAGPOLE keyword are summarized below:

Syntax:	`CO FLAGPOLE (Flagdf)`
Type:	`Optional, Non-repeatable`

where Flagdf is an optional parameter to specify a default flagpole receptor height. If no parameter is provided, then a default flagpole receptor height of 0.0 meters is used. Any flagpole receptor heights that are entered on the Receptor pathway will override the default value, but are ignored if the FLAGPOLE keyword is not present on the Control pathway, and a non-fatal warning message is generated.

3.2.8 To Run or Not to Run - That is the Question

Because of the improved error handling and the "defensive programming" that has been employed in the design of the AERMOD model, it is intended that the model will read through all of the inputs in the runstream file regardless of any errors or warnings that may be encountered. If a fatal error occurs in processing of the runstream information, then further model calculations will be aborted. Otherwise, the model will attempt to run. Because of the great many options available in the AERMOD model, and the potential for wasted resources if a large run is performed with some incorrect input data, the RUNORNOT keyword has been included on the Control pathway to allow the user to specify whether to RUN the model and perform all of the

calculations, or NOT to run and only process the input runstream data and summarize the setup information. The syntax and type of the RUNORNOT keyword are summarized below:

Syntax:	`CO RUNORNOT  RUN or NOT`
Type:	`Mandatory, Non-repeatable`

3.2.9 Generating an Input File for EVENT Processing

The AERMOD model contains the EVENTFIL keyword on the CO pathway to control whether or not the AERMOD model will generate an input file for EVENT processing. The syntax and type of the EVENTFIL keyword are summarized below:

Syntax:	`CO EVENTFIL  (Evfile)  (Evopt)`
Type:	`Optional, Non-repeatable`

where the optional Evfile parameter specifies the name of the EVENT input file to be generated (the maximum length of the file name is set by the ILEN_FLD parameter in MODULE MAIN1), and the optional parameter, Evopt, specifies the level of detail to be used in the EVENT output file. Valid inputs for the Evopt parameter are the secondary keywords of SOCONT and DETAIL (see the EVENTOUT keyword on the OUtput pathway, Section 3.7.2). The default filename used if no parameters are specified is EVENTS.INP, and the default for the level of detail is DETAIL. If only one parameter is present, then it is taken to be the Evfile, and the default will be used for Evopt.

The primary difference between routine AERMOD and EVENT processing is in the treatment of source group contributions. The AERMOD model treats the source groups independently. EVENT processing is designed to provide source contributions to particular events, such as the design concentrations determined from AERMOD, or user specified events. The user may specify the "events" to process using the EVent pathway, which lists specific combinations of receptor location, source group, and averaging period. By specifying the EVENTFIL keyword, an input runstream file will be generated that can be used directly for

EVENT processing. The events included in the generated EVENT processing input file are the design concentrations defined by the RECTABLE keyword and the threshold violations identified by the MAXIFILE keyword on the OU pathway.

3.2.10 The Model Re-start Capability

The AERMOD model has an optional capability to store intermediate results into an unformatted file, so that the model run can be continued later in case of a power failure or a user interrupt. This re-start option is controlled by the SAVEFILE and INITFILE keywords on the CO pathway. The syntax and type of these keywords are summarized below:

Syntax:	`CO SAVEFILE (Savfil) (Dayinc) (Savfl2)` `CO INITFILE (Inifil)`
Type:	`Optional, Non-repeatable`

The SAVEFILE keyword instructs the model to save the intermediate results to a file, and controls the save options. All three parameters for this keyword are optional. If the user specifies only the Savfil parameter, then the intermediate results are saved to the same file (and overwritten) each time. If the user specifies both the Savfil and the Savfl2 parameters, then the model alternates between the two files for storing intermediate results. The latter approach requires additional disk space to handle two storage files. However, selecting two files avoids the potential problem that the power failure or interrupt might occur while the temporary file is open and the intermediate results are being copied to it. In such a case, the temporary results file would be lost.

The optional Dayinc parameter allows the user to specify the number of days between successive dumps. The default is to dump values at the end of each day, i.e., Dayinc = 1. For larger modeling runs, where the SAVEFILE option is most useful, the additional execution time required to implement this option is very small compared to the total runtime. To be most effective, it is recommended that results be saved at least every 5 days.

If no parameters are specified for the SAVEFILE keyword, then the model will store intermediate results at the end of each day using a default filename of TMP.FIL.

The INITFILE keyword works in conjunction with the SAVEFILE keyword, and instructs the model to initialize the results arrays from a previously saved file. The optional parameter, Inifil, identifies the unformatted file of intermediate results to use for initializing the model. If no Inifil parameter is specified, then the model assumes the default filename of TMP.FIL. If the file doesn't exist or if there are any errors encountered in opening the file, then a fatal error message is generated and processing is halted.

Note: It is important to note that if both the SAVEFILE and INITFILE keywords are used in a the same model run, then different filenames must be specified for the Savfil and Inifil parameters. Otherwise, the model will encounter an error in opening the files, and further processing will be halted.

3.2.11 Post-1997 PM_{10} Processing

A new NAAQS for modeling PM_{10} was promulgated in July 1997. This guidance utilizes the expected second high value of the 24-hour NAAQS replaced by a 3-year average of the 99th percentile value of the frequency distribution and a 3-year average of the annual mean. Since the Guideline on Air Quality Modeling precludes the use of a 3-year data set, a policy was established that uses unbiased estimates of the 3-year averages, utilizing all meteorological data (both single and multiple years of data) available. An unbiased estimate of the 99th percentile is the fourth highest concentration, if one year of meteorological data are input to the model, or the multi-year average of the fourth highest concentrations, if more than one year of meteorological data are input to the model. Similarly, an unbiased estimate of the 3-year average annual mean is simply the annual mean, if only one year of meteorological data are input to the model, or the multi-year average annual mean if multiple years of meteorological data are used. Analogously to the original NAAQS situation, the entire area is in compliance when the highest fourth high (or highest average fourth high) and the highest annual mean (or the highest average annual mean) are less than or equal to the NAAQS.

AERMOD will process the 24-hour and annual averages for PM_{10} according to the new NAAQS if the pollutant ID specified on the CO POLLUTID card is PM10 or PM-10, and the CO MULTYEAR card is <u>not</u> present. In this case, the model will compute an average of the fourth highest concentrations at each receptor across the number of years of meteorological data being processed. For a single year of data, the model will report the fourth highest concentration at each receptor. For a five year period of data, the model will report the average of the five fourth-highest values at each receptor. Also, for multiple year data files, the annual average will first be calculated for each individual year of data, and the average of these across the number of years will be calculated. This processing of the annual average across multiple years may give slightly different results than the PERIOD average across the same time period, due to differences in the number of calms from year to year. In order to accommodate this difference, the new PM_{10} NAAQS makes use of the ANNUAL average keyword for specifying the long-term average.

Users should be aware of the following restrictions which are applied to the new PM_{10} NAAQS processing.

1. The averaging periods are limited to the 24-hour and ANNUAL averages. Use of the PERIOD average or a short-term average other than 24-hour will result in a fatal error message being generated.

2. Only the FOURTH (or 4TH) highest value may be requested on the RECTABLE card for 24-hour averages. Specifying another high value on the RECTABLE card will result in a fatal error message being generated.

3. The model will only process complete years of meteorological data, although there is no restriction on the start date for the data. If less than one complete year of data is processed, a fatal error message will be generated. If additional meteorological data remains after the end of the last complete year of data, the remaining data will be ignored, and a non-fatal warning message will be generated specifying the number of hours ignored.

4. The MULTYEAR card cannot be used with the new PM_{10} NAAQS. Multiple year analyses should be accomplished by including the multiple years of meteorology in a single data file.

5. Since the 24-hour average design values for post-1997 PM_{10} analyses may consist of averages over a multi-year period, they are incompatible with the EVENT processor. If the MAXIFILE option is used to output 24-hour average threshold violations, these may be used with the EVENT processor. Therefore, if the EVENTFIL option is used without the MAXIFILE option for post-1997 PM_{10} analyses, a non-fatal warning message will be generated, and the EVENTFIL option will be ignored.

3.2.12 Pre-1997 PM_{10} Processing

AERMOD may still be used to perform PM_{10} analyses according to the pre-1997 NAAQS. This may be accomplished as before by use of the MULTYEAR card on the CO pathway, except that the syntax for this keyword has been changed slightly. The syntax and type are now as follows:

Syntax:	`CO MULTYEAR H6H Savfil (Inifil)`
Type:	`Optional, Non-repeatable`

where H6H is a new secondary keyword that identifies this as a pre-1997 analysis, the Savfil parameter specifies the filename for saving the results arrays at the end of each year of processing, and the Inifil parameter specifies the filename to use for initializing the results arrays at the beginning of the current year. The Inifil parameter is optional, and should be left blank for the first year in the multi-year series of runs. A non-fatal warning message will be generated if the MULTYEAR card is used for pre-1997 NAAQS analyses.

3.2.13 Debugging Output Option

The DEBUGOPT keyword on the CO pathway allows the user to request detailed files of intermediate calculation results for debugging purposes. The syntax and type of the DEBUGOPT keyword are summarized below:

Syntax:	`CO DEBUGOPT MODEL (Dbgfil) and/or METEOR (Dbmfil)`
Type:	`Optional, Non-repeatable`

where the MODEL and METEOR secondary keywords specify the type of debug information to be provided, and the Dbgfil and Dbmfil parameters specify the names of the detailed message files. This option allows for two types of debug output files. The MODEL secondary keyword specifies that intermediate calculations related to the model results for each source and receptor, e.g., dispersion parameters, plume heights, etc., are to be output. The METEOR secondary keyword specifies that the gridded profiles of meteorological variables for each hour of data are to be output. Use the DEBUGOPT keyword with **CAUTION**: it can produce very large files! The METEOR profiles are printed to a separate file from the MODEL information. The filenames for each type of output are optional, and if provided must immediately follow the appropriate secondary keyword. The default filenames used if none are specified by the user are MODEL.DBG and METEOR.DBG. The model will overwrite these files, without warning, if they already exist.

3.2.14 Detailed Error Listing File

The ERRORFIL keyword on the CO pathway allows the user to request a detailed listing file of all the messages generated by the model. This includes the error and warning messages that are listed as part of the message summaries provided in the main output file, and also any informational messages (such as occurrences of calm winds) and quality assurance messages that are generated. The syntax and type of the ERRORFIL keyword are summarized below:

Syntax:	`CO ERRORFIL  (Errfil)`
Type:	`Optional, Non-repeatable`

where the Errfil parameter is the name of the detailed message file. If the optional Errfil parameter is left blank, then the model will use a default filename of ERRORS.LST. A complete description of the error and other types of messages generated by the model is provided in Appendix C.

3.3 SOURCE PATHWAY INPUTS AND OPTIONS

The **SO**urce pathway contains the keywords that define the source information for a particular model run. The model currently handles three source types, identified as point, volume or area sources. The input parameters vary depending on the source type. For point sources, the user can also identify building dimensions for nearby structure that cause aerodynamic downwash influences on the source. The user can also identify groups of sources for which the model will combine the results.

The LOCATION keyword, which identifies the source type and location, must be the first card entered for each source. The only other requirement for order of the keywords is that the SRCGROUP keyword must be the last keyword before the SO FINISHED card. The user may group all of the LOCATION cards together, then group the source parameter cards together, or they may want to group all input cards for a particular source together. All sources are given a source ID by the user, which is used to link the source parameter inputs to the correct source or sources. The source ID can be any alphanumeric string of up to eight characters.

As noted in Section 2.3, the number of sources is allocated dynamically at the time AERMOD is run. This value, in concert with the other dynamically allocated arrays and input requirements, is limited only by the amount of available memory.

3.3.1 Identifying Source Types and Locations

The LOCATION keyword is used to identify the source type and the location of each source to be modeled. The LOCATION card must be the first card entered for each source since it identifies the source type, and dictates which parameters are needed and/or accepted. The syntax, type and order of the LOCATION keyword are summarized below:

Syntax:	`SO LOCATION Srcid Srctyp Xs Ys (Zs)`
Type:	`Mandatory, Repeatable`
Order:	`Must be first card for each source input`

where the Srcid parameter is the alphanumeric source ID defined by the user (up to eight characters), Srctyp is the source type, which is identified by one of the secondary keywords - POINT, VOLUME, AREA, AREAPOLY, or AREACIRC - and Xs, Ys, and Zs are the x, y, and z coordinates of the source location in meters. All three of the area source types use the same numerical integration algorithm for estimating impacts from area sources, and are merely different options for specifying the shape of the area source. The AREA source keyword may be used to specify a rectangular-shaped area source with arbitrary orientation; the AREAPOLY source keyword may be used to specify an area source as an irregularly-shaped polygon of up to 20 sides; and the AREACIRC source keyword may be used to specify a circular-shaped area source (modeled as an equal-area polygon of 20 sides). Note that the source elevation, Zs, is an optional parameter. If the default option to include elevated terrain effects is used and the source elevation is omitted, a warning message will be generated and the source elevation will be given a value of 0.0. The source elevation is not used by the model if the non-default FLAT terrain option is used. While the default units of Zs are meters, the user may also specify source elevations to be in feet by adding the SO ELEVUNIT FEET card immediately following the SO STARTING card. The x (east-west) and y (north-south) coordinates are for the center of the source for POINT, VOLUME, and AREACIRC sources, and are for one of the vertices of the source for AREA and AREAPOLY sources. The source coordinates may be input as Universal Transverse Mercator (UTM) coordinates, or may be referenced to a user-defined origin.

Certain types of line sources can be handled in AERMOD using either a string of volume sources, or as an elongated area source. The volume source algorithms are most applicable to line sources with some initial plume depth, such as conveyor belts and rail lines. Section 1.2.2 of the ISC Model User's Guide - Volume II (EPA, 1995) provides technical information on how to model a line source with multiple volume sources. The use of the AERMOD area source algorithm for elongated rectangles would be most applicable to near ground level line sources, such as a viaduct.

The source ID entered on the LOCATION card identifies that source for the remainder of the SO pathway inputs. Since the model accepts alphanumeric strings of up to eight characters for the source ID, the sources can be identified with descriptive names, such as STACK1, STACK2, BOILER3, SLAGPILE, etc. This may also be useful if line sources are being modeled as multiple volume or areas, as discussed above. Since they are part of the same physical source, they can be given names that will identify them as being related, such as LINE1A, LINE1B, LINE1C, etc.

3.3.2 Specifying Source Release Parameters

The main source parameters are input on the SRCPARAM card, which is a mandatory keyword for each source being modeled. Since the input parameters vary depending on the source type, the different source types handled by the AERMOD model are discussed separately.

3.3.2.1 POINT Source Inputs.

The AERMOD POINT source algorithms are used to model releases from stacks and isolated vents, as well as other kinds of sources. The syntax, type and order for the SRCPARAM card for POINT sources are summarized below:

Syntax:	`SO SRCPARAM  Srcid Ptemis Stkhgt Stktmp Stkvel Stkdia`
Type:	`Mandatory, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

where the Srcid parameter is the same source ID that was entered on the LOCATION card for a particular source, and the other parameters are as follows:

Ptemis - point emission rate in g/s,

Stkhgt - release height above ground in meters,

Stktmp - stack gas exit temperature in degrees K,

Stkvel - stack gas exit velocity in m/s, and

Stkdia - stack inside diameter in meters.

An example of a valid SRCPARAM input card for a point source is given below:

```
SO SRCPARAM  STACK1  16.71  35.0  444.0  22.7  2.74
```

where the source ID is STACK1, the emission rate is 16.71 g/s, the release height is 35.0 m, the exit temperature is 444.0 K, the exit velocity is 22.7 m/s, and the inside stack diameter is 2.74 m. All of the parameters must be present on the input card.

If a value of 0.0 is input for the exit temperature, AERMOD will adjust the exit temperature for each hour to match the ambient temperature. This option allows the user to model a plume that is released at ambient temperature. The user may also model a plume with an exit temperature that exceeds the ambient temperature by a fixed amount by entering a negative value for exit temperature equal in magnitude to the temperature difference. The model will add the absolute value of a negative exit temperature to the ambient temperature for each hour to obtain the exit temperature used in computing the buoyancy flux of the plume. The AERMOD model does not include algorithms to model plumes that are released at temperatures below ambient temperature. Such releases should be modeled with a dense gas model.

Since the AERMOD model uses direction-specific building dimensions for all sources subject to building downwash, there are no building parameters entered on the SRCPARAM card. Building dimensions are entered on the BUILDHGT, BUILDWID, BUILDLEN, XBADJ, and YBADJ cards described below in Section 3.3.3.

3.3.2.2 VOLUME Source Inputs.

The AERMOD VOLUME source algorithms are used to model releases from a variety of industrial sources, such as building roof monitors, multiple vents, and conveyor belts. The syntax, type and order for the SRCPARAM card for VOLUME sources are summarized below:

Syntax:	`SO SRCPARAM  Srcid Vlemis Relhgt Syinit Szinit`
Type:	`Mandatory, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

where the Srcid parameter is the same source ID that was entered on the LOCATION card for a particular source, and the other parameters are as follows:

Vlemis - volume emission rate in g/s,

Relhgt - release height (center of volume) above ground, in meters,

Syinit - initial lateral dimension of the volume in meters, and

Szinit - initial vertical dimension of the volume in meters.

The following table, which is explained in more detail in Section 1.2.2 of the ISC Model User's Guide - Volume II, summarizes the suggested procedures to be used for estimating the initial lateral and vertical dimensions for various types of volume and line sources.

TABLE 3-1.

SUMMARY OF SUGGESTED PROCEDURES FOR ESTIMATING INITIAL LATERAL DIMENSIONS σ_{yo} AND INITIAL VERTICAL DIMENSIONS σ_{zo} FOR VOLUME AND LINE SOURCES

Type of Source		Procedure for Obtaining Initial Dimension
(a) Initial Lateral Dimensions (σ_{yo})		
Single Volume Source	σ_{yo} =	length of side divided by 4.3
Line Source Represented by Adjacent Volume Sources (see Figure 1-8(a) in EPA, 1995)	σ_{yo} =	length of side divided by 2.15
Line Source Represented by Separated Volume Sources (see Figure 1-8(b) in EPA, 1995)	σ_{yo} =	center to center distance divided by 2.15
(b) Initial Vertical Dimensions (σ_{zo})		
Surface-Based Source ($h_e \sim 0$)	σ_{zo} =	vertical dimension of source divided by 2.15
Elevated Source ($h_e > 0$) on or Adjacent to a Building	σ_{zo} =	building height divided by 2.15
Elevated Source ($h_e > 0$) not on or Adjacent to a Building	σ_{zo} =	vertical dimension of source divided by 4.3

3.3.2.3 AREA Source Inputs

The AERMOD area source algorithm is used to model low level or ground level releases with no plume rise (e.g., storage piles, slag dumps, and lagoons). The AERMOD model uses a numerical integration approach for modeling impacts from area sources. When the TOXICS option is specified, the area source integration routine is optimized to reduce model runtime. This is accomplished by incorporation of a three-tiered approach using the Romberg numerical integration, a 2-point Gaussian Quadrature routine for numerical integration, or a point source approximation based on the location of the receptor relative to the source. In the regulatory default mode the Romberg numerical integration is utilized for all receptors.

The AERMOD model includes three options for specifying the shape of an area source: the AREA source type may be used to specify rectangular areas that may also have a rotation angle specified relative to a north-south orientation; the AREAPOLY source type may be used to specify an area source as an irregularly-shaped polygon of up to 20 sides; and the AREACIRC source keyword may be used to specify a circular-shaped area source (modeled as an equal-area polygon of 20 sides). The source parameter inputs for each of the area source types is described below.

AREA Source Type

The rotation angle for rectangular AREA sources is specified relative to the vertex used to define the source location on the SO LOCATION card (e.g., the southwest corner). The syntax, type and order for the SRCPARAM card for AREA sources are summarized below:

Syntax:	`SO SRCPARAM  Srcid Aremis Relhgt Xinit (Yinit) (Angle) (Szinit)`
Type:	`Mandatory, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

where the Srcid parameter is the same source ID that was entered on the LOCATION card for a particular source, and the other parameters are as follows:

Aremis - area emission rate in g/(s-m^2),

Relhgt - release height above ground in meters,

Xinit - length of X side of the area (in the east-west direction if Angle is 0 degrees) in meters,

Yinit - length of Y side of the area (in the north-south direction if Angle is 0 degrees) in meters (optional),

Angle - orientation angle for the rectangular area in degrees from North, measured positive in the clockwise direction (optional), and

Szinit - initial vertical dimension of the area source plume in meters (optional).

It should be noted that the emission rate for the area source is an emission rate per unit area, which is different from the point and volume source emission rates, which are total emissions for the source.

If the optional Yinit parameter is omitted, then the model assumes that the area is a square, i.e., Yinit = Xinit. If the optional Angle parameter is omitted, then the model assumes that the area is oriented in the north-south and east-west directions, i.e., Angle = 0.0. If the Angle parameter is input, and the value does not equal 0.0, then the model will rotate the area clockwise around the vertex defined on the SO LOCATION card for this source. Figure 3-1 illustrates the relationship between the Xinit, Yinit, and Angle parameters and the source location, (Xs,Ys), for a rotated rectangle. The Xinit dimension is measured from the side of the area that is counterclockwise along the perimeter from the vertex defined by (Xs,Ys), while the Yinit dimension is measured from the side of the area that is clockwise from (Xs,Ys). The Angle parameter is measured as the orientation relative to North of the side that is clockwise from (Xs,Ys), i.e. the side with length Yinit. The Angle parameter may be positive (for clockwise rotation) or negative (for counterclockwise rotation), and a warning message is generated if the absolute value of Angle is greater than 180 degrees. The selection of the vertex to use for the source location is not critical, as long as the relationship described above for the Xinit, Yinit, and Angle parameters is maintained.

FIGURE 3-1. RELATIONSHIP OF AREA SOURCE PARAMETERS FOR ROTATED RECTANGLE

By making the Yinit and Angle parameters optional, the area source input data for the previous versions of the ISC2 model can be used with the AERMOD model. The aspect ratio (i.e., length/width) for area sources should generally be less than about 10 to 1. If this is exceeded, then the model will generate a non-fatal warning message, and the user should consider subdividing the area to achieve a 10 to 1 aspect ratio (or less) for all subareas.

The optional Szinit parameter may be used to specify an initial vertical dimension to the area source plume, similar to the use of the Szinit parameter for volume sources. This parameter may be important when the area source algorithm is used to model mechanically generated emission sources, such as mobile sources. In these cases, the emissions may be turbulently mixed near the source by the process that is generating the emissions, and therefore occupy some initial depth. For more passive area source emissions, such as evaporation or wind erosion, the Szinit parameter may be omitted, which is equivalent to using an initial sigma-z of zero.

An example of a valid SRCPARAM input card for a rectangular area source is given below:

```
SO SRCPARAM  SLAGPILE  0.0015  5.0  50.0  100.0  30.0
```

where the source ID is SLAGPILE, the emission rate is 0.0015 g/(s-m^2), the release height is 5.0 m, the X-dimension is 50.0 m, the Y-dimension is 100.0 m, and the orientation angle is 30.0 degrees clockwise from North.

Since the numerical integration algorithm can handle elongated areas with aspect ratios of up to 10 to 1, the AERMOD area source algorithm may be useful for modeling certain types of line sources. There are no restrictions on the placement of receptors relative to area sources for the AERMOD model. Receptors may be placed within the area and at the edge of an area. The AERMOD model will integrate over the portion of the area that is upwind of the receptor. However, since the numerical integration is not performed for portions of the area that are closer than 1.0 meter upwind of the receptor, caution should be used when placing receptors within or

adjacent to areas that are less than a few meters wide. More technical information about the application of the AERMOD area source algorithm is provided in Sections 1.2.3 and 2.2.3 of the ISC Model User's Guide - Volume II (EPA, 1995).

AREAPOLY Source Type

The AREAPOLY source type may be used to specify an area source as an arbitrarily-shaped polygon of between 3 and 20 sides (the number of sides allowed may be increased by modifying the NVMAX parameter in MODULE MAIN1). This source type option provides the user with considerable flexibility for specifying the shape of an area source. The syntax, type and order for the SRCPARAM card for AREAPOLY sources are summarized below:

Syntax:	`SO SRCPARAM  Srcid Aremis Relhgt Nverts (Szinit)`
Type:	`Mandatory, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

where the Srcid parameter is the same source ID that was entered on the LOCATION card for a particular source, and the other parameters are as follows:

Aremis - area emission rate in g/(s-m^2),

Relhgt - release height above ground in meters,

Nverts - number of vertices (or sides) of the area source polygon,

Szinit - initial vertical dimension of the area source plume in meters (optional).

As with AREA sources, the emission rate for the source is an emission rate per unit area, which is different from the point and volume source emission rates, which are total emissions for the source. The number of vertices (or sides) used to define the area source polygon may vary between 3 and 20. The locations of the vertices are specified by use of the AREAVERT keyword, which applies only to AREAPOLY sources. The syntax, type and order for the AREAVERT keyword used for AREAPOLY sources are summarized below:

Syntax:	SO AREAVERT Srcid Xv(1) Yv(1) Xv(2) Yv(2) ... Xv(i) Yv(i)
Type:	Mandatory for AREAPOLY sources, Repeatable
Order:	Must follow the LOCATION card for each source input

where the Xv(i) and Yv(i) are the x-coordinate and y-coordinate values of the vertices of the area source polygon. There must by Nverts pairs of coordinates for the area source, where Nverts in the number of vertices specified for that source on the SRCPARAM card. The first vertex, Xv(1) and Yv(1), must also match the coordinates given for the source location on the LOCATION card, Xs and Ys. The remaining vertices may be defined in either a clockwise or counter-clockwise order from the point used for defining the source location.

Since the numerical integration algorithm can handle elongated areas with aspect ratios of up to 10 to 1, the AERMOD area source algorithm may be useful for modeling certain types of line sources. There are no restrictions on the placement of receptors relative to area sources for the AERMOD model. Receptors may be placed within the area and at the edge of an area. The AERMOD model will integrate over the portion of the area that is upwind of the receptor. However, since the numerical integration is not performed for portions of the area that are closer than 1.0 meter upwind of the receptor, caution should be used when placing receptors within or adjacent to areas that are less than a few meters wide.

AREACIRC Source Type

The AREACIRC source type may be used to specify an area source as a circular shape. The model will automatically generate a regular polygon of up to 20 sides to approximate the circular area source. The polygon will have the same area as that specified for the circle. The syntax, type and order for the SRCPARAM card for AREACIRC sources are summarized below:

Syntax:	SO SRCPARAM Srcid Aremis Relhgt Radius (Nverts) (Szinit)
Type:	Mandatory, Repeatable
Order:	Must follow the LOCATION card for each source input

where the Srcid parameter is the same source ID that was entered on the LOCATION card for a particular source, and the other parameters are as follows:

Aremis - area emission rate in g/(s-m^2),

Relhgt - release height above ground in meters,

Radius - radius of the circular area in meters,

Nverts - number of vertices (or sides) of the area source polygon (optional, 20 sides will be used if omitted),

Szinit - initial vertical dimension of the area source plume in meters (optional).

As with AREA sources, the emission rate for the source is an emission rate per unit area, which is different from the point and volume source emission rates, which are total emissions for the source.

3.3.3 Specifying Building Downwash Information

As noted above, the AERMOD model include algorithms to model the effects of buildings downwash on emissions from nearby or adjacent point sources. The building downwash algorithms do not apply to volume or area sources. For a technical description of the building downwash algorithms in AERMOD, the user is referred to Schulman, et. al. (2000). The AERMOD model uses direction-specific information for all building downwash cases.

There are five keywords that are used to specify building downwash information: BUILDHGT, BUILDWID, BUILDLEN, XBADJ, YBADJ. The syntax, type and order for the BUILDHGT keyword, used to input direction specific building heights, are summarized below:

Syntax:	`SO BUILDHGT  Srcid (or Srcrng) Dsbh(i),i=1,36 (16 for LT)`
Type:	`Optional, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

where the Srcid parameter is the same source ID that was entered on the LOCATION card for a particular source. The user also has the option of specifying a range of sources (the Srcrng parameter) for which the building heights apply, instead of identifying a single source. This is accomplished by two source ID character strings separated by a dash, e.g., STACK1-STACK10. Since the model reads the source range as a single input field there must not be any spaces between the source IDs. The model then places the building heights that follow (the Dsbh(i) parameter) into the appropriate arrays for all Srcid's that fall within that range, including STACK1 and STACK10.

When comparing a source ID to the range limits for a Srcrng parameter, the model separates the source IDs into three parts: an initial alphabetical part, a numerical part, and then the remainder of the string. Each part is then compared to the corresponding parts of the source range, and all three parts must satisfy the respective ranges in order for the source ID to be included. If there is no numeric part, then the ID consists of only one alphabetical part. If the ID begins with a numeric character, then the initial alphabetical part defaults to a single blank. If there is no trailing alphabetical part, then the third part also defaults to a single blank part. If the trailing part consists of more than one alphabetical or numeric field, it is all lumped into one character field. For example, the source ID 'STACK2' consists of the parts 'STACK' plus '2' plus a single trailing blank, ' '. By comparing the separate parts of the source IDs, it can be seen that STACK2 falls between the range 'STACK1-STACK10.' For a three-part example, it can also be seen that VENT1B falls within the range of VENT1A-VENT1C. However, VENT2 does not fall within the range of VENT1A to VENT3B, since the third part of VENT2 is a single blank, which does not fall within the range of A to C. This is because a blank character will precede a normal alphabetical character. Normally, the source ranges will work as one would intuitively expect for simple source names. Most importantly, for names that are made up entirely of numeric characters, the source ranges will be based simply on the relative numerical values. The user is strongly encouraged to check the summary of model inputs to ensure that the source ranges were interpreted as expected, and also to avoid using complex source names in ranges, such as AA1B2C-AB3A3C. Since the order of keywords within the SO pathway is quite flexible, it is also important to note that the building heights will only be applied to those sources that have been defined previously in the input file.

Following the Srcid or the Srcrng parameter, the user inputs 36 direction-specific building heights (Dsbh parameter) in meters, beginning with the 10 degree flow vector (wind blowing toward 10 degrees from north), and incrementing by 10 degrees in a clockwise direction. Some examples of building height inputs are presented below:

```
SO BUILDHGT  STACK1  34. 34. 34. 34. 34. 34. 34. 34. 34. 34. 34. 34.
SO BUILDHGT  STACK1  34. 34. 34. 34. 34. 34. 34. 34. 34. 34. 34. 34.
SO BUILDHGT  STACK1  34. 34. 34. 34. 34. 34. 34. 34. 34. 34. 34. 34.

SO BUILDHGT  STACK1  36*34.0

SO BUILDHGT  STACK1-STACK10  33*34.0  3*0.0

SO BUILDHGT  STACK1  35.43 36.45 36.37 35.18 32.92 29.66 25.50 20.56
SO BUILDHGT  STACK1  15.00 20.56 25.50 29.66 32.92 35.18 36.37 36.45
SO BUILDHGT  STACK1  35.43 33.33 35.43 36.45  0.00 35.18 32.92 29.66
SO BUILDHGT  STACK1  25.50 20.56 15.00 20.56 25.50 29.66 32.92 35.18
SO BUILDHGT  STACK1  36.37 36.45 35.43 33.33
```

The first example illustrates the use of repeat cards if more than one card is needed to input all of the values. The values are processed in the order in which they appear in the input file, and are identified as being repeat cards by repeating the Srcid parameter. The first and second examples produce identical results within the model. The second one illustrates the use of a repeat value that can simplify numerical input in some cases. The field "36*34.0" is interpreted by the model as "repeat the value 34.0 a total of 36 times." This is also used in the third example where the building height is constant for directions of 10 degrees through 330 degrees, and then is set to 0.0 (e.g. the stack may be outside the region of downwash influence) for directions 340 through 360. The third example also uses a source range rather than a single source ID. The last example illustrates building heights which vary by direction, and shows that the number of values on each card need not be the same. For improved readability of the input file, the user may want to put the numerical inputs into "columns," but there are no special rules regarding the spacing of the parameters on this keyword.

The BUILDWID keyword is used to input direction-specific building widths for downwash analyses. The syntax for this keyword, which is very similar to the BUILDHGT keyword, is summarized below, along with the type and order information:

Syntax:	`SO BUILDWID  Srcid (or Srcrng) Dsbw(i),i=1,36  (16 for LT)`
Type:	`Optional, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

For a description of the Srcid and Srcrng parameters, and for a discussion and examples of the numeric input options, refer to the BUILDHGT keyword above. The Dsbw(i) parameter contains the 36 direction-specific building widths. The directions proceed in a clockwise direction, beginning with the 10 degree flow vector.

The BUILDLEN keyword is used to input direction-specific along-flow building lengths for downwash analyses. Figure 3-2 shows the relationship of the projected building to this dimension. The syntax for this keyword, which is very similar to the BUILDHGT keyword, is summarized below, along with the type and order information:

Syntax:	`SO BUILDLEN  Srcid (or Srcrng) Dsbl(i),i=1,36`
Type:	`Optional, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

For a description of the Srcid and Srcrng parameters, and for a discussion and examples of the numeric input options, refer to the BUILDHGT keyword above. The Dsbl(i) parameter contains the 36 direction-specific building lengths. The directions proceed in a clockwise direction, beginning with the 10 degree flow vector.

Figure 3-2 shows the relationship of the projected building to these distances.

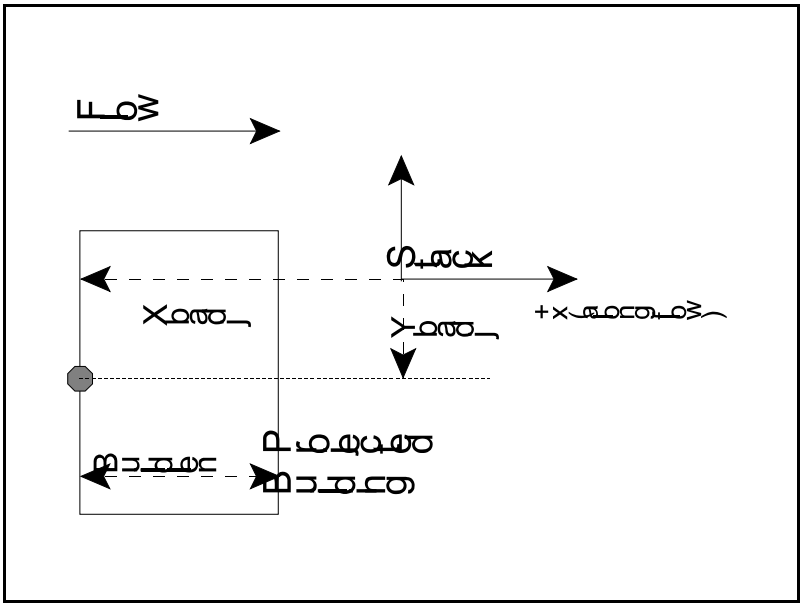

FIGURE 3-2. SCHEMATIC DIAGRAM IDENTIFYING NEW BUILDING DATA FOR PRIME DOWNWASH

The XBADJ and YBADJ keywords are used to input direction-specific along-flow and across-flow distances from the stack to the center of the upwind face of the projected building, respectively. Figure 3-2 shows the relationship of the projected building to these distances. The syntax for these keywords, which is very similar to the BUILDHGT keyword, are summarized below, along with the type and order information:

Syntax:	`SO XBADJ  Srcid (or Srcrng) Xbadj(i),i=1,36`
Type:	`Optional, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

Syntax:	`SO YBADJ  Srcid (or Srcrng) Ybadj(i),i=1,36`
Type:	`Optional, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

For a description of the Srcid and Srcrng parameters, refer to the BUILDHGT keyword above. The Xbadj(i) parameter contains the 36 direction-specific along-flow distances from the stack to the center of the upwind face and the Ybadj(i) parameter contains the 36 direction-specific across-flow distances from the stack to the center of the upwind face. The directions proceed in a clockwise direction, beginning with the 10 degree flow vector.

3.3.4 Specifying Urban Sources

As discussed in Section 3.2.4, the AERMOD model allows the user to incorporate the effects of increased surface heating from an urban area on pollutant dispersion under stable atmospheric conditions. The user specifies the parameters for the urban area on the CO URBANOPT card (see Section 3.2.4), and identifies which sources are to be modeled with urban effects using the SO URBANSRC card. If a source is not included on the URBANSRC card, it will be modeled without the urban effects. The syntax, type and order for the URBANSRC keyword are summarized below:

Syntax:	`SO URBANSRC  Srcid's  and/or  Srcrng's`
Type:	`Optional, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

where the Srcid's and Srcrng's are the individual source IDs and/or source ranges that are to be modeled with urban effects. Source ranges, which are described in more detail in the description of the BUILDHGT keyword (Section 3.3.3), are input as two source IDs separated by a dash, e.g.,

STACK1-STACK10. Individual source IDs and source ranges may be used on the same card. If more than one input card is needed to define the urban sources, then additional cards may be input.

3.3.5 Using Variable Emission Rates

The AERMOD model provide the option of specifying variable emission rate factors for individual sources or for groups of sources. The factors may vary on different time scales, such as by season, hour-of-day, etc. The EMISFACT keyword provides the user the option of specifying variable emission rate factors for sources modeled by the AERMOD model. The syntax, type and order of this keyword are summarized below:

Syntax:	`SO EMISFACT  Srcid (or Srcrng)  Qflag  Qfact(i),i=1,n`
Type:	`Optional, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

where the Srcid parameter is the same source ID that was entered on the LOCATION card for a particular source. The user also has the option of using the Srcrng parameter for specifying a range of sources for which the emission rate factors apply, instead of identifying a single source. This is accomplished by two source ID character strings separated by a dash, e.g., STACK1-STACK10. The use of the Srcrng parameter is explained in more detail in Section 3.3.3 above for the BUILDHGT keyword.

The parameter Qflag is the variable emission rate flag, and is one of the following secondary keywords:

SEASON - emission rates vary seasonally (n=4),

MONTH - emission rates vary monthly (n=12),

HROFDY - emission rates vary by hour-of-day (n=24),

WSPEED - emission rates vary by wind speed (n=6),

SEASHR- emission rates vary by season and hour-of-day (n=96),

SHRDOW - emission rates vary by season, hour-of-day, and day-of-week [M-F, Sat., Sun.] (n=288), and

SHRDOW7 - emission rates vary by season, hour-of-day, and the seven days of the week [M,Tu,W,Th,F,Sat.,Sun.] (n=672).

The Qfact array is the array of factors, where the number of factors is shown above for each Qflag option. The seasons are defined in the following order: Winter (Dec., Jan., Feb.), Spring (Mar., Apr., May), Summer (Jun., Jul., Aug.), and Fall (Sep., Oct., Nov.). The wind speed categories used with the WSPEED option may be defined using the ME WINDCATS keyword. If the WINDCATS keyword is not used, the default wind speed categories are defined by the upper bound of the first five categories as follows (the sixth category is assumed to have no upper bound): 1.54, 3.09, 5.14, 8.23, and 10.8 m/s. The EMISFACT card may be repeated as many times as necessary to input all of the factors, and repeat values may be used for the numerical inputs. An example of each of these options is presented below, with column headers to indicate the order in which values are to be to input:

```
**                          WINTER  SPRING  SUMMER  FALL
SO EMISFACT STACK1 SEASON   0.50    0.50    1.00   0.75
**                         JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
SO EMISFACT STACK1 MONTH  0.1 0.2 0.3 0.4 0.5 0.5 0.5 0.6 0.7 1.0 1.0 1.0
**                          1   2   3   4   5   6   7   8   9  10  11  12
SO EMISFACT STACK1 HROFDY  0.0 0.0 0.0 0.0 0.0 0.5 1.0 1.0 1.0 1.0 1.0 1.0

**                         13  14  15  16  17  18  19  20  21  22  23  24
SO EMISFACT STACK1 HROFDY  1.0 1.0 1.0 1.0 1.0 0.5 0.0 0.0 0.0 0.0 0.0 0.0


** or, equivalently:        1-5    6    7-17   18   19-24
SO EMISFACT STACK1 HROFDY  5*0.0  0.5  11*1.0  0.5  6*0.0
**        Wind Speed Cat.:   1      2      3      4      5      6
SO EMISFACT STACK1 WSPEED   0.5    0.6    0.7    0.8    0.9    1.0
SO EMISFACT STACK1 SEASHR  enter 24 hourly scalars for each of the four
                           seasons (winter, spring, summer, fall), e.g.,

**                           Winter    Spring    Summer     Fall
SO EMISFACT STACK1 SEASHR    24*0.50   24*0.50   24*1.00   24*0.75
SO EMISFACT STACK1 SHRDOW  enter 24 hourly scalars for each of the four
                           seasons (winter, spring, summer, fall), first
                           for Weekdays (Monday-Friday), then for Saturdays,
                           and finally for Sundays, e.g.,

** Weekdays:                 Winter    Spring    Summer     Fall
SO EMISFACT STACK1 SHRDOW    24*1.0    24*0.8    24*0.6    24*0.8
** Saturdays:
SO EMISFACT STACK1 SHRDOW    24*0.5    24*0.4    24*0.3    24*0.4
** Sundays:
SO EMISFACT STACK1 SHRDOW    24*0.25   24*0.2    24*0.15   24*0.2
SO EMISFACT STACK1 SHRDOW7 enter 24 hourly scalars for each of the four
                           seasons (winter, spring, summer, fall), first
                           for Mondays, then for Tuesdays, ..., then for Saturdays,
                           and finally for Sundays, e.g.,

** Mondays:                  Winter    Spring    Summer     Fall
SO EMISFACT STACK1 SHRDOW7   24*1.0    24*0.8    24*0.6    24*0.8
** Tuesdays:                 Winter    Spring    Summer     Fall
       .
       .
       .
** Saturdays:
SO EMISFACT STACK1 SHRDOW7   24*0.5    24*0.4    24*0.3    24*0.4
** Sundays:
SO EMISFACT STACK1 SHRDOW7   24*0.25   24*0.2    24*0.15   24*0.2
```

3.3.6 Adjusting the Emission Rate Units for Output

The default emission rate units for the AERMOD model are grams per second for point and volume sources, and grams per second per square meter for area sources. By default, the model converts these input units to output units of micrograms per cubic meter for concentration calculations. This is accomplished by applying a default emission rate unit factor of 1.0E06 for concentration.

The EMISUNIT keyword on the SO pathway allows the user to specify a different unit conversion factor, and to specify the appropriate label for the output units for either concentration calculations. The syntax and type of the EMISUNIT keyword are summarized below:

Syntax:	`SO EMISUNIT  Emifac  Emilbl  Conlbl`
Type:	`Optional, Non-repeatable`

where the parameter Emifac is the emission rate unit factor, Emilbl is the label for the emission units (up to 40 characters), and Conlbl is the output unit label (up to 40 characters) for concentration calculations. For example, to produce output concentrations in milligrams per cubic meter, assuming input units of grams per sec, the following card could be input:

```
SO EMISUNIT  1.0E3  GRAMS/SEC   MILLIGRAMS/M**3
```

since there are 1.0E3 milligrams per gram. The emission rate unit factor applies to all sources for a given run. Since the model uses one or more spaces to separate different fields on the input runstream images, it is important that there not be any spaces within the label fields on this card. Thus, instead of entering 'GRAMS PER SECOND' for the emission label, a label of 'GRAMS/SECOND', or 'GRAMS-PER-SECOND' or an equivalent variation should be used.

3.3.7 Specifying Variables for Settling, Removal and Deposition Calculations

The current version of the AERMOD model does not include algorithms to handle the gravitational settling and removal by dry deposition of particulates.

3.3.8 Specifying Variables for Precipitation Scavenging and Wet Deposition Calculations

The current version of the AERMOD model does not include algorithms to handle the scavenging and removal by wet deposition (i.e., precipitation scavenging) of gases and particulates.

3.3.9 Specifying an Hourly Emission Rate File

The source (SO) pathway includes an option for inputting hourly emission rates for the AERMOD model, controlled by the HOUREMIS keyword. AERMOD currently allows for a single hourly emission file to be used with each model run. The syntax, type and order for this keyword are summarized below:

Syntax:	`SO HOUREMIS  Emifil  Srcid's (and/or Srcrng's)`
Type:	`Optional, Repeatable`
Order:	`Must follow the LOCATION card for each source input`

where the Emifil parameter specifies the filename (up to 40 characters) for the hourly emission file, and Srcid or Srcrng identify the source or sources for which hourly emission rates are included. Source ranges, which are described in more detail in the description of the BUILDHGT keyword (Section 3.3.3), are input as two source IDs separated by a dash, e.g., STACK1-STACK10. The user may include more than one HOUREMIS card in a runstream file, if needed to specify additional sources, but there can be only one hourly emissions file, and therefore the filename must be the same on all HOUREMIS cards.

The format of each record of the hourly emissions file includes a pathway and keyword (SO HOUREMIS), followed by the Year, Month, Day, Hour, Source ID, and emission rate (in the appropriate units). For point sources, the stack gas exit temperature (K), and stack gas exit velocity (m/s) are also specified. The hourly emissions file is processed using the same routines used to process the runstream input file, therefore each of the parameters must be separated by at least one space, but otherwise the format is flexible. It is also not necessary to include the SO HOUREMIS on each line, as long as the parameters (Year, Month, etc.) do not begin before column 13.

The data in the hourly emission file must include the exact same dates as are included in the meteorological input files, and the source IDs must correspond to the source IDs defined on the SO LOCATION cards and be in the same order. Multiple records are required to define the emissions for one hour if more than one source is referenced. The model will check for a date mismatch between the hourly emissions file and the meteorological data, and also for a source ID mismatch. However, it is not necessary to process the entire hourly emissions file on each model run, i.e., the correct emissions data will be read if the ME DAYRANGE or the ME STARTEND cards (see Section 3.5.4) are used, as long as all the dates (including those that are processed and those that are skipped) match the meteorological data files. An example of several lines from an hourly emissions file for two point sources is provided below:

```
SO HOUREMIS  88  8 16  1  STACK1  52.467   382.604   12.27
SO HOUREMIS  88  8 16  1  STACK2  44.327   432.326   22.17
SO HOUREMIS  88  8 16  2  STACK1  22.321   377.882   9.27
SO HOUREMIS  88  8 16  2  STACK2  42.166   437.682   19.67
SO HOUREMIS  88  8 16  3  STACK1  51.499   373.716   11.87
SO HOUREMIS  88  8 16  3  STACK2  41.349   437.276   18.77
SO HOUREMIS  88  8 16  4  STACK1  36.020   374.827   9.63
SO HOUREMIS  88  8 16  4  STACK2  43.672   437.682   18.23
```

The model will use the stack release height and stack inside diameter defined on the SO SRCPARAM card, but will use the emission rate, exit temperature and exit velocity from the hourly emission file. If the emission rate, exit temperature and exit velocity are not included for a particular hour, i.e, any or all of those fields are blank, the model will interpret emissions data for

that hour as missing and will set the parameters to zero. Since the emission rate will be zero, there will be no calculations made for that hour and that source.

3.3.10 Including Source Data From an External File

The user has the option of including source data from an external file by using the INCLUDED keyword on the source (SO) pathway. An SO INCLUDED card may be placed anywhere within the source pathway, after the STARTING card and before the FINISHED card (i.e., the SO STARTING and SO FINISHED cards cannot be included in the external file). The data in the included file will be processed as though it were part of the runstream file. The syntax and type of the INCLUDED keyword are summarized below:

Syntax:	`SO INCLUDED  Incfil`
Type:	`Optional, Repeatable`

where the Incfil parameter is a character field of up to 40 characters that identifies the filename for the included file. The contents of the included file must be valid runstream images for the source pathway. If an error is generated during processing of the included file, the error message will report the line number of the included file (see Appendix C). If more than one INCLUDED file is specified for the source pathway, the user will first need to determine which file the error occurred in. If the starting column of the main runstream input file is shifted from column 1 (see Section 2.4.8), then the runstream images in the included file must be offset by the same amount.

3.3.11 Using Source Groups

The AERMOD model allows the user to group contributions from particular sources together. Several source groups may be setup in a single run, and they may, for example, be used to model impacts from the source being permitted, the group of increment consuming PSD sources, and the group of all sources for comparison to a NAAQS in a single run. There is always at least one source group in a run, which may consist of all sources, so the SRCGROUP keyword

has been made mandatory in the AERMOD model. The syntax, type and order of the SRCGROUP keyword are summarized below:

Syntax:	`SO SRCGROUP  Grpid  Srcid's  and/or  Srcrng's`
Type:	`Mandatory, Repeatable`
Order:	`Must be the last keyword in the SO pathway before FINISHED`

where the Grpid parameter is an alphanumeric string of up to eight characters that identifies the group name. The Srcid's and Srcrng's are the individual source IDs and/or source ranges that make up the group of sources. Source ranges, which are described in more detail in the description of the BUILDHGT keyword (Section 3.3.3), are input as two source IDs separated by a dash, e.g., STACK1-STACK10. Individual source IDs and source ranges may be used on the same card. If more than one input card is needed to define the sources for a particular group, then additional cards may be input, repeating the pathway, keyword and group ID.

A special group ID has been reserved for use in specifying the group of <u>all</u> sources. When Grpid = <u>ALL</u>, the model will automatically setup a source group called <u>ALL</u> that includes all sources modeled for that particular run. If desired, the user can setup a group of all sources with a different group ID by explicitly specifying all sources on the input card(s).

As noted in Section 2.3, the number of source groups is allocated dynamically at the time AERMOD is run. This value, in concert with the other dynamically allocated arrays and input requirements, is limited only by the amount of available memory.

As discussed in Sections 1.2.4.6 and 3.2.9, it is sometimes important for a user to know the contribution of a particular source to the total result for a group. These source contribution analyses are facilitated for short term averages by the use the EVENT processing capabilities in the AERMOD model. EVENT processing uses the same source groups that are identified by AERMOD (when the input file is generated using the CO EVENTFIL option), but the model is structured in a way that it retains individual source results for particular events. Refer to the sections noted above for a more complete description of EVENT processing and its uses.

3.4 RECEPTOR PATHWAY INPUTS AND OPTIONS

The **RE**ceptor pathway contains keywords that define the receptor information for a particular model run. The RE pathway contains keywords that allow the user to define Cartesian grid receptor networks and/or polar grid receptor networks, with either uniform or non-uniform grid spacing, as well as discrete receptor locations referenced to a Cartesian or a polar system. As noted in Section 2.3, the number of receptors and receptor networks are allocated dynamically at the time AERMOD is run. This value, in combination with the other dynamically allocated arrays and input requirements, is limited only by the amount of available memory.

All of the receptor options in AERMOD allow the user to input terrain elevations and hill height scales for each receptor, both of which are needed when applying AERMOD in an elevated terrain situation. To facilitate the generation of hill height scales for AERMOD, a terrain preprocessor, called AERMAP, has been developed (EPA, 2004c). The AERMAP terrain preprocessor, which uses U.S. Geological Survey (USGS) Digital Elevation Model (DEM) data as an input, may also be used to generate the terrain elevations for the receptor locations. The AERMAP program generates an output file that contains the receptor pathway data for AERMOD in the format described below. This file may either be cut and pasted into the AERMOD runstream file, or may be included as an external file using the RE INCLUDED card (see Section 3.4.4).

The default units for receptor elevations for the AERMOD model are in meters, however, the user may specify receptor elevations to be in units of feet by adding the RE ELEVUNIT FEET card immediately after the RE STARTING card. Since the AERMAP terrain preprocessor outputs elevations in meters and includes the RE ELEVUNIT METERS card as the first record, the AERMAP data must be placed at the beginning of the receptor pathway.

3.4.1 Defining Networks of Gridded Receptors

Two types of receptor networks are allowed by the AERMOD model. A Cartesian grid network, defined through the GRIDCART keyword, includes an array of points identified by their

x (east-west) and y (north-south) coordinates. A polar network, defined by the GRIDPOLR keyword, is an array of points identified by direction and distance from a user-defined origin. Each of these keywords has a series of secondary keywords associated with it that are used to define the network, including any receptor elevations for elevated terrain and flagpole receptor heights. The GRIDCART and GRIDPOLR keywords can be thought of as "sub-pathways," since their secondary keywords include a STArt and an END card to define the start and end of inputs for a particular network.

3.4.1.1 Cartesian Grid Receptor Networks.

Cartesian grid receptor networks are defined by use of the GRIDCART keyword. The GRIDCART keyword may be thought of as a "sub-pathway," in that there are a series of secondary keywords that are used to define the start and the end of the inputs for a particular network, and to select the options for defining the receptor locations that make up the network. The syntax and type of the GRIDCART keyword are summarized below:

Syntax:	`RE GRIDCART Netid STA`
	`XYINC Xinit Xnum Xdelta Yinit Ynum Ydelta`
	`or XPNTS Gridx1 Gridx2 Gridx3 .... Gridxn, and`
	`YPNTS Gridy1 Gridy2 Gridy3 .... Gridyn`
	`ELEV Row Zelev1 Zelev2 Zelev3 ... Zelevn`
	`HILL Row Zhill1 Zhill2 Zhill3 ... Zhilln`
	`FLAG Row Zflag1 Zflag2 Zflag3 ... Zflagn`
	`END`

Type:	`Optional, Repeatable`

where the parameters are defined as follows:

Netid	Receptor network identification code (up to eight alphanumeric characters)
STA	Indicates the STArt of GRIDCART inputs for a particular network, repeated for each new Netid
XYINC Xinit Xnum Xdelta Yinit Ynum Ydelta	Keyword identifying uniform grid network generated from x and y increments Starting x-axis grid location in meters Number of x-axis receptors Spacing in meters between x-axis receptors Starting y-axis grid location in meters Number of y-axis receptors Spacing in meters between y-axis receptors
XPNTS Gridx1 Gridxn	Keyword identifying grid network defined by a series of discrete x and y coordinates (used with YPNTS) Value of first x-coordinate for Cartesian grid (m) Value of 'nth' x-coordinate for Cartesian grid (m)
YPNTS Gridy1 Gridyn	Keyword identifying grid network defined by a series of discrete x and y coordinates (used with XPNTS) Value of first y-coordinate for Cartesian grid (m) Value of 'nth' y-coordinate for Cartesian grid (m)
ELEV Row Zelev	Keyword to specify that receptor elevations follow (optional) Indicates which row (y-coordinate fixed) is being input (Row=1 means first, i.e., southmost row) An array of receptor terrain elevations (m) for a particular Row (default units of meters may be changed to feet by use of RE ELEVUNIT keyword), number of entries per row equals the number of x-coordinates for that network
HILL Row Zelev	Keyword to specify that hill height scales follow (optional) Indicates which row (y-coordinate fixed) is being input (Row=1 means first, i.e., southmost row) An array of hill height scales (m) for a particular Row (default units of meters may be changed to feet by use of RE ELEVUNIT keyword), number of entries per row equals the number of x-coordinates for that network
FLAG Row Zflag	Keyword to specify that flagpole receptor heights follow (optional) Indicates which row (y-coordinate fixed) is being input (Row=1 means first, i.e., southmost row) An array of receptor heights (m) above local terrain elevation for a particular Row (flagpole receptors), number of entries per row equals the number of x-coordinates for that network
END	Indicates the END of GRIDCART inputs for a particular network, repeated for each new Netid

The ELEV, HILL, and FLAG keywords are optional inputs, and are only needed if elevated terrain or flagpole receptor heights are to be used. If elevated terrain is being used, then both the ELEV and HILL inputs are needed for each receptor. If the ELEV and HILL keywords are used and the model is being run with the flat terrain option (see Section 3.2.2), then the elevated terrain height inputs will be ignored by the model, and a non-fatal warning message will be generated. If the elevated terrain option is selected, and no elevated terrain heights are entered,

the elevations will default to 0.0 meters, and warning messages will also be generated. The model handles flagpole receptor height inputs in a similar manner.

The order of cards within the GRIDCART subpathway is not important, as long as all inputs for a particular network are contiguous and start with the STA secondary keyword and end with the END secondary keyword. It is not even required that all ELEV cards be contiguous, although the input file will be more readable if a logical order is followed. The network ID is also not required to appear on each runstream image (except for the STA card). The model will assume the previous ID if none is entered, similar to the use of continuation cards for pathway and keywords. Thus, the following two examples produce the same 8 X 4 Cartesian grid network:

```
RE GRIDCART CAR1 STA
RE GRIDCART CAR1 XPNTS  -500.  -400.  -200.  -100. 100.  200.  400.  500.
RE GRIDCART CAR1 YPNTS  -500.  -250.   250.  500.
RE GRIDCART CAR1 ELEV  1  10.  10.  10.  10.  10.  10. 10.  10.
RE GRIDCART CAR1 ELEV  2  20.  20.  20.  20.  20.  20. 20.  20.
RE GRIDCART CAR1 ELEV  3  30.  30.  30.  30.  30.  30. 30.  30.
RE GRIDCART CAR1 ELEV  4  40.  40.  40.  40.  40.  40. 40.  40.
RE GRIDCART CAR1 HILL  1  50.  50.  50.  50.  50.  50. 50.  50.
RE GRIDCART CAR1 HILL  2  60.  60.  60.  60.  60.  60. 60.  60.
RE GRIDCART CAR1 HILL  3  70.  70.  70.  70.  70.  70. 70.  70.
RE GRIDCART CAR1 HILL  4  80.  80.  80.  80.  80.  80. 80.  80.
RE GRIDCART CAR1 FLAG  1  10.  10.  10.  10.  10.  10. 10.  10.
RE GRIDCART CAR1 FLAG  2  20.  20.  20.  20.  20.  20. 20.  20.
RE GRIDCART CAR1 FLAG  3  30.  30.  30.  30.  30.  30. 30.  30.
RE GRIDCART CAR1 FLAG  4  40.  40.  40.  40.  40.  40. 40.  40.
RE GRIDCART CAR1 END
```

```
RE GRIDCART CAR1 STA
                 XPNTS  -500.  -400.  -200.  -100. 100.  200.  400.  500.
                 YPNTS  -500.  -250.   250.  500.
                 ELEV  1  8*10.
                 HILL  1  8*50.
                 FLAG  1  8*10.
                 ELEV  2  8*20.
                 HILL  2  8*60.
                 FLAG  2  8*20.
                 ELEV  3  8*30.
                 HILL  3  8*70.
                 FLAG  3  8*30.
                 ELEV  4  8*40.
                 HILL  4  8*80.
                 FLAG  4  8*40.
RE GRIDCART CAR1 END
```

The Row parameter on the ELEV, HILL, and FLAG inputs may be entered as either the row number, i.e., 1, 2, etc., or as the actual y-coordinate value, e.g., -500., -250., etc. in the example above. The model sorts the inputs using Row as the index, so the result is the same. The

above example could therefore be entered as follows, with the same result:

```
RE GRIDCART CAR1 STA
                 XPNTS  -500.  -400.  -200.  -100.  100.  200.  400.  500.
                 YPNTS  -500.  -250.   250.  500.
                 ELEV  -500.  8*10.
                 FLAG  -500.  8*10.
                 ELEV  -250.  8*20.
                 FLAG  -250.  8*20.
                 ELEV   250.  8*30.
                 FLAG   250.  8*30.
                 ELEV   500.  8*40.
                 FLAG   500.  8*40.
RE GRIDCART CAR1 END
```

Of course, one must use either the row number or y-coordinate value consistently within each network to have the desired result.

The following simple example illustrates the use of the XYINC secondary keyword to generate a uniformly spaced Cartesian grid network. The resulting grid is 11 x 11, with a uniform spacing of 1 kilometer (1000. meters), and is centered on the origin (0., 0.). No elevated terrain heights or flagpole receptor heights are included in this example.

```
RE GRIDCART CG1 STA
                XYINC  -5000.  11  1000.  -5000.  11 1000.
RE GRIDCART CG1 END
```

3.4.1.2 Polar Grid Receptor Networks.

Polar receptor networks are defined by use of the GRIDPOLR keyword. The GRIDPOLR keyword may also be thought of as a "sub-pathway," in that there are a series of secondary keywords that are used to define the start and the end of the inputs for a particular network, and to select the options for defining the receptor locations that make up the network. The syntax and type of the GRIDPOLR keyword are summarized below:

Syntax:	`RE GRIDPOLR Netid STA`
	`ORIG Xinit Yinit,`
	`or ORIG Srcid`
	`DIST Ring1 Ring2 Ring3 ... Ringn`
	`DDIR Dir1 Dir2 Dir3 ... Dirn,`
	`or GDIR Dirnum Dirini Dirinc`
	`ELEV Dir Zelev1 Zelev2 Zelev3 ... Zelevn`
	`HILL Dir Zhill1 Zhill2 Zhill3 ... Zhilln`
	`FLAG Dir Zflag1 Zflag2 Zflag3 ... Zflagn`
	`END`

Type:	`Optional, Repeatable`

where the parameters are defined as follows:

Netid	Receptor network identification code (up to eight alphanumeric characters)
STA	Indicates STArt of GRIDPOLR inputs for a particular network, repeat for each new Netid
ORIG Xinit Yinit Srcid	Keyword to specify the origin of the polar network (optional) x-coordinate for origin of polar network y-coordinate for origin of polar network Source ID of source used as origin of polar network
DIST Ring1 Ringn	Keyword to specify distances for the polar network Distance to the first ring of polar coordinates Distance to the 'nth' ring of polar coordinates
DDIR Dir1 Dirn	Keyword to specify discrete direction radials for the polar network First direction radial in degrees (1 to 360) The 'nth' direction radial in degrees (1 to 360)
GDIR Dirnum Dirini Dirinc	Keyword to specify generated direction radials for the polar network Number of directions used to define the polar system Starting direction of the polar system Increment (in degrees) for defining directions
ELEV Dir Zelev	Keyword to specify that receptor elevations follow (optional) Indicates which direction is being input An array of receptor terrain elevations for a particular direction radial (default units of meters may be changed to feet by use of RE ELEVUNIT keyword), number of entries per radial equals the number of distances for that network
HILL Dir Zelev	Keyword to specify that hill height scales follow (optional) Indicates which direction is being input An array of receptor hill height scales for a particular direction radial (default units of meters may be changed to feet by use of RE ELEVUNIT keyword), number of entries per radial equals the number of distances for that network
FLAG Dir Zflag	Keyword to specify that flagpole receptor heights follow (optional) Indicates which direction is being input An array of receptor heights above local terrain elevation for a particular direction (flagpole receptors)
END	Indicates END of GRIDPOLR subpathway, repeat for each new Netid

The ORIG secondary keyword is optional for the GRIDPOLR inputs. If omitted, the model assumes a default origin of (0., 0.,) in x,y coordinates. The ELEV, HILL, and FLAG keywords are also optional inputs, and are only needed if elevated terrain or flagpole receptor heights are to be used. If elevated terrain is being used, then both the ELEV and HILL inputs are needed for each receptor. If the ELEV and HILL keywords are used and the model is being run with the flat terrain option (see Section 3.2.2), then the elevated terrain height inputs will be ignored by the model, and a non-fatal warning message will be generated. If the elevated terrain

option is selected, and no elevated terrain heights are entered, the elevations will default to 0.0 meters, and warning messages will also be generated. The model handles flagpole receptor height inputs in a similar manner.

As with the GRIDCART keyword described above, the order of cards within the GRIDPOLR subpathway is not important, as long as all inputs for a particular network are contiguous and start with the STA secondary keyword and end with the END secondary keyword. It is not even required that all ELEV cards be contiguous, although the input file will be more readable if a logical order is followed. The network ID is also not required to appear on each runstream image (except for the STA card). The model will assume the previous ID if none is entered, similar to the use of continuation cards for pathway and keywords.

The following example of the GRIDPOLR keyword generates a receptor network consisting of 180 receptor points on five concentric distance rings centered on an assumed default origin of (0.,0.). The receptor locations are placed along 36 direction radials, beginning with 10. degrees and incrementing by 10. degrees in a clockwise fashion.

```
RE GRIDPOLR POL1 STA
                 DIST  100.  300.  500.  1000.  2000.
                 GDIR  36    10.   10.
RE GRIDPOLR POL1 END
```

Another example is provided illustrating the use of a non-zero origin, discrete direction radials and the specification of elevated terrain and flagpole receptor heights:

```
RE GRIDPOLR POL1 STA
                 ORIG  500.  500.
                 DIST  100.  300.  500.  1000.  2000.
                 DDIR  90.   180.  270.  360.
                 ELEV  90.   5. 10. 15. 20. 25.
                 ELEV  180.  5. 10. 15. 20. 25.
                 ELEV  270.  5. 10. 15. 20. 25.
                 ELEV  360.  5. 10. 15. 20. 25.
                 HILL  90.  50. 60. 75. 80. 95.
                 HILL  180. 50. 60. 75. 80. 95.
                 HILL  270. 50. 60. 75. 80. 95.
                 HILL  360. 50. 60. 75. 80. 95.
                 FLAG  90.   5. 10. 15. 20. 25.
                 FLAG  180.  5. 10. 15. 20. 25.
                 FLAG  270.  5. 10. 15. 20. 25.
                 FLAG  360.  5. 10. 15. 20. 25.
RE GRIDPOLR POL1 END
```

The user has the option of specifying the radial number (e.g. 1, 2, 3, etc.) on the ELEV, HILL, and FLAG inputs, or the actual direction associated with each radial.

For purposes of model calculations, all receptor locations, including those specified as polar, are stored in the model arrays as x, y and z coordinates and flagpole heights. For the purposes of reporting the results by receptor in the main print file, the tables are labeled with the polar inputs, i.e., directions and distances.

3.4.2 Using Multiple Receptor Networks

For some modeling applications, the user may need a fairly coarsely spaced network covering a large area to identify the area of significant impacts for a plant, and a denser network covering a smaller area to identify the maximum impacts. To accommodate this modeling need, the AERMOD model allows the user to specify multiple receptor networks in a single model run. The user can define either Cartesian grid networks or polar networks, or both. With the use of the ORIG option in the GRIDPOLR keyword, the user can easily place a receptor network centered on the facility being permitted, and also place a network centered on another background source known to be a significant contributor to high concentrations. Alternatively, the polar network may be centered on a receptor location of special concern, such as a nearby Class I area.

As noted in the introduction to this section (3.4), the model dynamically allocates array storage based on the number of receptors and receptor networks when the AERMOD model is run, up to the maximum amount of memory available on the computer.

3.4.3 Specifying Discrete Receptor Locations

In addition to the receptor networks defined by the GRIDCART and GRIDPOLR keywords described above, the user may also specify discrete receptor points for modeling impacts at specific locations of interest. This may be used to model critical receptors, such as the locations of schools or houses, nearby Class I areas, or locations identified as having high concentrations by previous modeling analyses. The discrete receptors may be input as either

Cartesian x,y points (DISCCART keyword) or as polar distance and direction coordinates (DISCPOLR keyword). Both types of receptors may be identified in a single run. In addition, for discrete polar receptor points the user specifies the source whose location is used as the origin for the receptor.

3.4.3.1 Discrete Cartesian Receptors.

Discrete Cartesian receptors are defined by use of the DISCCART keyword. The syntax and type of this keyword are summarized below:

Syntax:	`RE DISCCART Xcoord Ycoord (Zelev Zhill) (Zflag)`
Type:	`Optional, Repeatable`

where the Xcoord and Ycoord parameters are the x-coordinate and y-coordinate (m), respectively, for the receptor location. The Zelev parameter is an optional terrain elevation (m) and Zhill is a corresponding hill height scale for the receptor for use in elevated terrain modeling. Both the Zelev and Zhill parameters must be specified for use with the elevated terrain algorithms, and are referenced to the same reference elevation (e.g., mean sea level) used for source elevations. The Zflag parameter is the optional receptor height above ground (m) for modeling flagpole receptors. All of the parameters are in units of meters, except for Zelev and Zhill, which default to meters but may be specified in feet by use of the RE ELEVUNIT keyword.

If neither the elevated terrain option (Section 3.2.2) nor the flagpole receptor height option (Section 3.2.7) are used, then the optional parameters are ignored if present. If only the elevated terrain height option is used (no flagpoles), then the third parameter (the field after the Ycoord) is read as the Zelev parameter. If only the flagpole receptor height option is used (no elevated terrain), then the third parameter is read as the Zflag parameter. If both options are used, then the parameters are read in the order indicated for the syntax above. If the optional parameters are left blank, then default values will be used. The default value for Zelev is 0.0, and the default value for Zflag is defined by the CO FLAGPOLE card (see Section 3.2.7). Note: If both the elevated terrain and flagpole receptor height options are used, then the third parameter will always be used

as Zelev, and it is not possible to use a default value for Zelev while entering a specific value for the Zflag parameter.

3.4.3.2 Discrete Polar Receptors.

Discrete polar receptors are defined by use of the DISCPOLR keyword. The syntax and type of this keyword are summarized below:

Syntax:	`RE DISCPOLR Srcid Dist Direct (Zelev Zhill) (Zflag)`
Type:	`Optional, Repeatable`

where the Srcid is the alphanumeric source identification for one of the sources defined on the SO pathway which will be used to define the origin for the polar receptor location. The Dist and Direct parameters are the distance in meters and direction in degrees for the discrete receptor location. Degrees are measured clockwise from north. The Zelev parameter is an optional terrain elevation for the receptor and Zhill is the corresponding hill top elevation (m) for use in elevated terrain modeling. Both the Zelev and Zhill parameters must be specified for use with the elevated terrain algorithms, and are referenced to the same reference elevation (e.g., mean sea level) used for source elevations. The units of Zelev and Zhill are in meters, unless specified as feet by the RE ELEVUNIT keyword. The Zflag parameter is the optional receptor height above ground (meters) for modeling flagpole receptors.

If neither the elevated terrain option (Section 3.2.2) nor the flagpole receptor height option (Section 3.2.7) are used, then the optional parameters are ignored if present. If only the elevated terrain height option is used (no flagpoles), then the third parameter (the field after the Ycoord) is read as the Zelev parameter. If only the flagpole receptor height option is used (no elevated terrain), then the third parameter is read as the Zflag parameter. If both options are used, then the parameters are read in the order indicated for the syntax above. If the optional parameters are left blank, then default values will be used. The default value for Zelev is 0.0, and the default value for Zflag is defined by the CO FLAGPOLE card (see Section 3.2.7). Note: If both the elevated terrain and flagpole receptor height options are used, then fourth parameter will always be used as

Zelev, and it is not possible to use a default value for Zelev while entering a specific value for the Zflag parameter.

3.4.3.3 Discrete Cartesian Receptors for EVALFILE Output.

The EVALCART keyword is used to define discrete Cartesian receptor locations, similar to the DISCCART keyword, but it also allows for grouping of receptors, e.g., along arcs. It is designed to be used with the EVALFILE option, described later for the output pathway, which outputs arc maxima values to a separate file for evaluation purposes. The EVALCART keyword can be used without the use of the EVALFILE option, in which case the receptor groupings are ignored. The syntax and type for the modified EVALCART keyword are summarized below:

Syntax:	`RE EVALCART Xcoord Ycoord Zelev Zhill Zflag Arcid (Name)`
Type:	`Optional, Repeatable`

where the Xcoord and Ycoord parameters are the x-coordinate and y-coordinate (m), respectively, for the receptor location. The Zelev parameter is the terrain elevation (m) for the receptor and Zhill is the corresponding hill top elevation (m) for use in elevated terrain modeling. Both the Zelev and Zhill parameters must be specified for use with the elevated terrain algorithms, and are referenced to the same reference elevation (e.g., mean sea level) used for source elevations. The Zflag parameter is the receptor height above ground (m) for modeling flagpole receptors. All of the parameters are in units of meters, except for Zelev and Zhill, which default to meters but may be specified in feet by use of the RE ELEVUNIT keyword. The Arcid parameter is the receptor grouping identification, which may be up to eight characters long, and may be used to group receptors by arc. The Name parameter is an optional name field that may be included to further identify a particular receptor location. The Name parameter is ignored by the model. Unlike the DISCCART keyword, all of the parameters (except for the Name) must be present on each card with the EVALCART keyword. The terrain height and flagpole height inputs are ignored if the appropriate options are not specified on the CO TERRHGHT and CO FLAGPOLE cards.

3.4.4 Including Receptor Data From an External File

The user has the option of including receptor data from an external file by using the INCLUDED keyword on the receptor pathway. An RE INCLUDED card may be placed anywhere within the source pathway, after the STARTING card and before the FINISHED card (i.e., the RE STARTING and RE FINISHED cards cannot be included in the external file). The data in the included file will be processed as though it were part of the runstream file. The syntax and type of the INCLUDED keyword are summarized below:

Syntax:	`RE INCLUDED  Incfil`
Type:	`Optional, Repeatable`

where the Incfil parameter is a character field of up to 40 characters that identifies the filename for the included file. The contents of the included file must be valid runstream images for the receptor pathway. If an error is generated during processing of the included file, the error message will report the line number of the included file (see Appendix C). If more than one INCLUDED file is specified for the receptor pathway, the user will first need to determine which file the error occurred in. If the starting column of the main runstream input file is shifted from column 1 (see Section 2.4.8), then the runstream images in the included file must be offset by the same amount. The INCLUDED option allows the user to include receptor data that have been generated by the AERMOD Terrain Preprocessor, AERMAP, in the runstream file without having to cut and paste the AERMAP output file. Since AERMAP generates terrain elevations in meters and includes the RE ELEVUNIT METERS card as the first record, an AERMAP file must be INCLUDED at the beginning of the receptor pathway, immediately following the RE STARTING card. If more than one AERMAP output file is INCLUDED on the receptor pathway, the RE ELEVUNIT METERS card must be deleted from all but the first one.

3.5 METEOROLOGY PATHWAY INPUTS AND OPTIONS

The **ME**teorology pathway contains keywords that define the input meteorological data for a particular model run.

3.5.1 Specifying the Input Data Files and Formats

The AERMOD model uses hourly meteorological data from separate surface and profile data files as one of the basic model inputs. These input meteorological data filenames for AERMOD are identified by the SURFFILE and PROFFILE keywords on the ME pathway. The syntax and type of these keywords are summarized below:

Syntax:	`ME SURFFILE Sfcfil (Format)` `ME PROFFILE Profil (Format)`
Type:	`Mandatory, Non-repeatable`

where the Srcfil and Profil parameters are character fields of up to 40 characters that identify the filenames for the input meteorological data files. For running the model on an IBM-compatible PC, the filename parameters may include the complete DOS pathname for the file, or will assume the current directory if only the filename is given. The optional Format parameter specifies the format of the meteorological data files. The default formats for the surface and profile data files corresponds with the format of the files generated by the AERMET meteorological preprocessor program. The user also has the option of specifying the Fortran read format for each of these files. The contents of the meteorological data files are described below, and the file formats are documented in Appendix D.

The surface meteorological data file consists of a header record containing information on the meteorological station locations, and one record for each hour of data. These data are delimited by at least one space between each element, i.e., the data may be read as free format. The contents of the surface file are as follows:

Year
Month (1 - 12)
Day (1 -31)
Julian day (1 - 366)
Hour (1 - 24)
Sensible heat flux (W m^{-2})
Surface friction velocity, u_* (ms^{-1})
Convective velocity scale, w_* (ms^{-1})

Vertical potential temperature gradient in the 500 m layer above the planetary boundary layer
Height of the convectively-generated boundary layer (m)
Height of the mechanically-generated boundary layer (m)
Monin-Obukhov length, L (m)
Surface roughness length, z_0 (m)
Bowen ratio
Albedo
Wind speed (ms^{-1}) used in the computations
Wind direction (degrees) corresponding to the wind speed above
Height at which the wind above was measured (m)
Temperature (K) used in the computations
Height at which the temperature above was measured (m)

The sensible heat flux, Bowen ratio and albedo are not used by the AERMOD model, but are passed through by AERMET for information purposes only.

The profile meteorological data file consists of one or more records for each hour of data. As with the surface data file, the data are delimited by at least one space between each element and may be read as Fortran free format. The contents of the profile meteorological data file are as follows:

Year
Month (1 - 12)
Day (1 -31)
Hour (1 - 24)
Measurement height (m)
Top flag = 1, if this is the last (highest) level for this hour,
0, otherwise
Wind direction for the current level (degrees)
Wind speed for the current level (ms^{-1})
Temperature at the current level (K)
Standard deviation of the wind direction, σ_θ (degrees)
Standard deviation of the vertical wind speed, σ_w (ms^{-1})

The data in this file include the on-site meteorological data that are processed by AERMET. Since AERMET was designed to be able to perform dispersion parameter calculations with NWS data only, i.e., no on-site data, the profile data may consist of a one-level "profile" based on the NWS winds and temperature.

3.5.2 Specifying Station Information

Three keywords are used to specify information about the meteorological stations, SURFDATA for the surface meteorological station, UAIRDATA for the upper air station, and the optional SITEDATA for any on-site meteorological data that may be used. The syntax and type of these keywords are summarized below:

Syntax:	`ME SURFDATA Stanum Year (Name) (Xcoord) (Ycoord)`
Syntax:	`ME UAIRDATA Stanum Year (Name) (Xcoord) (Ycoord)`
Syntax:	`ME SITEDATA Stanum Year (Name) (Xcoord) (Ycoord)`
Type:	`Mandatory, Non-repeatable for SURFDATA and UAIRDATA` `Optional, Non-repeatable for SITEDATA`

where Stanum is the station number, e.g. the 5-digit WBAN number for NWS stations, Year is the year of data being processed (either 2 or 4 digits), Name is an optional character field (up to 40 characters with no blanks) specifying the name of the station, and Xcoord and Ycoord are optional parameters for specifying the x and y coordinates for the location of the stations. At the present time, the station locations are not utilized in the model. Therefore, no units are specified for Xcoord and Ycoord at this time, although meters are suggested in order to be consistent with the source and receptor coordinates. The AERMOD model compares the station numbers input using these keywords with the numbers included in the header record of the surface meteorological data file, and issues non-fatal warning messages if there are any mismatches.

3.5.3 Specifying the Base Elevation for Potential Temperature Profile

The AERMOD model generates a gridded vertical profile of potential temperatures for use in the plume rise calculations. Since potential temperature is dependent on the elevation above mean sea level (MSL), the user must define the base elevation for the profile with the PROFBASE keyword. The syntax and type for the PROFBASE keyword are summarized below:

Syntax:	`ME PROFBASE  BaseElev  (Units)`
Type:	`Mandatory, Non-repeatable`

where the BaseElev parameter specifies the base elevation above MSL for the potential temperature profile, and the optional Units parameter specifies the units of BaseElev. Valid inputs of Units are the secondary keywords METERS or FEET. The default units for BaseElev are in meters if Units is left blank. The base elevation should correspond with the base elevation of the primary meteorological tower.

3.5.4 Specifying a Data Period to Process

There are two keywords that allow the user to specify particular days or ranges of days to process from the sequential meteorological file input for the AERMOD model. The STARTEND keyword controls which period within the meteorological data file is read by the model, while the DAYRANGE keyword controls which days or ranges of days (of those that are read) for the model to process. The default for the model is to read the entire meteorological data file (up to a full year) and to process all days within that period.

The syntax and type for the STARTEND keyword are summarized below:

Syntax:	`ME STARTEND  Strtyr Strtmn Strtdy (Strthr) Endyr Endmn Enddy (Endhr)`
Type:	`Optional, Non-repeatable`

where the Strtyr Strtmn Strtdy parameters specify the year, month and day of the first record to be read (e.g., 87 01 31 for January 31, 1987), and the parameters Endyr Endmn Enddy specify the year, month and day of the last record to be read. The Strthr and Endhr are optional parameters that may be used to specify the start and end hours for the data period to be read. If either Strthr or Endhr is to be specified, then both must be specified. Any records in the data file that occur before the start date are ignored, as are any records in the data file that occur after the end date. In fact, once the end date has been reached, the model does not read any more data from the meteorological file. If Strthr and Endhr are not specified, then processing begins with hour 1 of

the start date, and ends with hour 24 of the end date, unless specific days are selected by the DAYRANGE card described below.

Any PERIOD averages calculated by the model will apply only to the period of data actually processed. Therefore, if someone wanted to calculate a six-month average, they could select PERIOD averages on the CO AVERTIME card, and then specify the period as follows:

```
ME STARTEND  87 01 01  87 06 30
```

for the period January 1, 1987 through June 30, 1987.

The syntax and type for the DAYRANGE keyword are summarized below:

Syntax:	`ME DAYRANGE  Range1  Range2  Range3  ... Rangen`
Type:	`Optional, Repeatable`

where the Range parameters specify particular days or ranges of days to process. The days may be specified as individual days (e.g. 1 2 3 4 5) or as a range of days (e.g. 1-5). The user also has the option of specifying Julian day numbers, from 1 to 365 (366 for leap years), or specifying month and day (e.g., 1/31 for January 31). Any combination of these may also be used. For example the following card will tell the model to process the days from January 1 (Julian day 1) through January 31 (1/31):

```
ME DAYRANGE  1-1/31
```

The DAYRANGE keyword is also repeatable, so that as many cards as needed may be included in the ME pathway.

As with the STARTEND keyword, any PERIOD averages calculated by the model will apply only to the period of data actually processed. If the STARTEND keyword is also used, then only those days selected on the DAYRANGE cards that fall within the period from the start date to the end date will be processed. Thus, if the ME pathway included the following two cards:

```
ME STARTEND  87 02 01  87 12 31
ME DAYRANGE  1-31
```

then no data would be processed, since the days 1 through 31 fall outside the period 2/1 to 12/31.

3.5.5 Correcting Wind Direction Alignment Problems

The WDROTATE keyword allows the user to correct the input meteorological data for wind direction alignment problems. All input wind directions or flow vectors are rotated by a user-specified amount. Since the model results at particular receptor locations are often quite sensitive to the transport wind direction, this optional keyword should be used only with extreme caution and with clear justification.

The syntax and type of this keyword are summarized below:

Syntax:	`ME WDROTATE  Rotang`
Type:	`Optional, Non-repeatable`

where the Rotang parameter specifies the angle in degrees to rotate the input wind direction measurements. The value of Rotang is subtracted from the wind direction measurements. It may be used to correct for known (and documented) calibration errors, or to adjust for the alignment of a valley if the meteorological station is located in a valley with a different alignment than the source location.

3.5.6 Specifying Wind Speed Categories

Variable emission rate factors may be input to the model that vary by wind speed category. The model uses six wind speed categories, and these are defined by the upper bound wind speed for the first five categories (the sixth category is assumed to have no upper bound). The default values for the wind speed categories are as follows: 1.54, 3.09, 5.14, 8.23, and 10.8 m/s. The syntax and type of the WINDCATS keyword, which may be used to specify different category boundaries, are summarized below:

Syntax:	`ME WINDCATS  Ws1  Ws2  Ws3  Ws4  Ws5`
Type:	`Optional, Non-repeatable`

where the Ws1 through Ws5 parameters are the upper bound wind speeds of the first through fifth categories in meters per second. The upper bound values are inclusive, i.e., a wind speed equal to the value of Ws1 will be placed in the first wind speed category.

3.5.7 Specifying SCIM Parameters

The SCIM parameters on the SCIMBYHR card specify the starting hour and sampling interval for the regular sample and an optional file name. The syntax and type of the SCIMBYHR keyword are summarized below:

Syntax:	`ME SCIMBYHR  NRegStart NRegInt NwetStart NwetInt (SfcFilnam PflFilnam)`
Type:	`Optional, Non-repeatable`

where the NRegStart and NRegInt parameters specify the first hour to be sampled and the sampling interval, respectively, when performing the regular sampling. The NWetStart and NWetInt parameters are used to specify the first wet hour (i.e., with non-zero precipitation) and the wet sampling interval for wet sampling. However, since the AERMOD model currently does not include wet deposition algorithms, the wet sampling option is not operational, and the user should enter a value of zero (0) for bot NWetStart and NWetInt. Optionally, the user can create

output files containing the surface and profile meteorological data for the sampled hours by specifying the SfcFilnam and PflFilnam parameters. These output files are in the same format used in the summary of the first 24 hours of data included in the main output file.

In order to use the SCIM option, the user must specify the non-DFAULT TOXICS option on the CO MODELOPT card, and also specify SCIM on the MODELOPT card. Although the ME SCIMBYHR is an optional card, it is required when using the SCIM option. NRegStart is required to have a value from 1 through 24, i.e., the first sampled hour must be on the first day in the meteorological data file. There are no restrictions for NRegInt; however, NRegInt would generally be greater than 1. For example, NRegInt could be based on the formula (24n+1), where "n" is the number of days to skip between samples, in order to ensure a regular diurnal cycle to the sampled hours (e.g., 25 or 49).

3.6 EVENT PATHWAY INPUTS AND OPTIONS

EVENT processing is specifically designed to facilitate analysis of source contributions to specific events for short term averages (less than or equal to 24 hours). These events may be design concentrations generated by the AERMOD model, occurrences of violations of an air quality standard, or user-specified events. These events are input to the AERMOD model through the **EV**ent pathway. Each event is defined by an averaging period and specific data period, a source group, and a receptor location. Since the locations are only of interest in combination with particular averaging and data periods, the REceptor pathway is not used with EVENT processing.

There are two keywords that are used to define the events on the EV pathway. The EVENTPER keyword defines the averaging period, data period and source group, while the EVENTLOC keyword defines the receptor location for the event. Each event is also given an alphanumeric name that links the two input cards for that event.

The syntax and type of the EVENTPER and EVENTLOC keywords are summarized below:

Syntax:	`EV EVENTPER  Evname  Aveper  Grpid  Date`
Syntax:	`EV EVENTLOC  Evname  XR= Xr  YR= Yr  (Zelev)  (Zflag)` `or  Evname  RNG= Rng  DIR= Dir (Zelev)  (Zflag)`
Type:	`Mandatory, Repeatable`

where the parameters are as follows:

Evname - event name (an alphanumeric string of up to 8 characters),

Aveper - averaging period for the event (e.g. 1, 3, 8, 24 hr)

Grpid - source group ID for the event (must be defined on SO pathway),

Date - date for the event, input as an eight digit integer for the ending hour of the data period (YYMMDDHH), e.g. 84030324 defines a data period ending at hour 24 on March 3, 1984. The length of the period corresponds to Aveper.

XR= - X-coordinate (m) for the event location, referenced to a Cartesian coordinate system

YR= - Y-coordinate (m) for the event location, referenced to a Cartesian coordinate system

RNG= - distance range (m) for the event location, referenced to a polar coordinate system with an origin of (0., 0.)

DIR= - radial direction (deg.) for the event location, referenced to a polar coordinate system with an origin of (0., 0.)

Zelev - optional terrain elevation for the event location (m)

Zflag - optional receptor height above ground (flagpole receptor) for the event location (m)

Each event is defined by the two input cards EVENTPER and EVENTLOC, and these inputs are linked by the event name, which must be unique among the events being processed in a given run. There is no particular requirement for the order of cards on the EV pathway. Note that the

location for the event may be specified by either Cartesian coordinates or by polar coordinates, however, the polar coordinates must be relative to an origin of (0,0).

3.6.1 Using Events Generated by the AERMOD Model

The AERMOD model has an option (CO EVENTFIL described in Section 3.2.9) to generate an input file for the AERMOD EVENT processing. When this option is used, the AERMOD model copies relevant inputs from the AERMOD runstream input file to the Event processing input file, and generates the inputs for the EVent pathway from the results of the modeling run. These events are the design concentrations identified by the OU RECTABLE keyword (see Section 3.8.1.1), such as the highest and high-second-high 24-hour averages, etc., and any threshold violations identified by the OU MAXIFILE keyword (see Section 3.8.1.2). The inputs generated by the AERMOD model correspond to the syntax described above for the EVENTPER and EVENTLOC keywords. The locations for events generated by the AERMOD model are always provided as Cartesian coordinates.

To easily identify the events generated by the AERMOD model, and to provide a mechanism for the AERMOD model to manage the events generated from the model run, a naming convention is used for the EVNAME parameter. The following examples illustrate the event names used by the AERMOD model:

H1H01001 - High-first-high 1-hour average for source group number 1

H2H24003 - High-second-high 24-hour average for source group number 3

TH030010 - Threshold violation number 10 for 3-hour averages

TH240019 - Threshold violation number 19 for 24-hour averages

The high value design concentrations are listed first in the EVENT processing input file, followed by the threshold violations (grouped by averaging period). To make it easier for the user to review the EVENT processing input file generated by the AERMOD model, and determine which events are of most concern, the actual concentration value associated with the event is included as

the last field on the EVENTPER card. This field is ignored by the AERMOD model, and is included only for informational purposes. The user should be aware that the same event may appear in the AERMOD model input file as both a design value and as a threshold violation, depending on the options selected and the actual results. Since the model processes the events by date sequence and outputs the results for each event as it is processed, the order of events in the output file will generally not follow the order of events in the input file, unless all of the events were generated by the MAXIFILE option.

3.6.2 Specifying Discrete Events

The user can specify discrete events by entering the EVENTPER and EVENTLOC cards as described above. The averaging period and source group selected for the event must be among those specified on the CO AVERTIME and SO SRCGROUP cards. If the EVENT processing input file was generated by the AERMOD model, the user may include additional events for those averaging periods and source groups used in the original AERMOD model run. They may also add averaging periods or define new source groups in the Event processing input file in order to define additional events.

3.6.3 Including Event Data From an External File

The user has the option of including event data from an external file by using the INCLUDED keyword on the source (EV) pathway. An EV INCLUDED card may be placed anywhere within the event pathway, after the STARTING card and before the FINISHED card (i.e., the EV STARTING and EV FINISHED cards cannot be included in the external file). The data in the included file will be processed as though it were part of the runstream file. The syntax and type of the INCLUDED keyword are summarized below:

Syntax:	`EV INCLUDED  Incfil`
Type:	`Optional, Repeatable`

where the Incfil parameter is a character field of up to 40 characters that identifies the filename for the included file. The contents of the included file must be valid runstream images for the event pathway. If an error is generated during processing of the included file, the error message will report the line number of the included file (see Appendix C). If more than one INCLUDED file is specified for the event pathway, the user will first need to determine which file the error occurred in. If the starting column of the main runstream input file is shifted from column 1 (see Section 2.4.8), then the runstream images in the included file must be offset by the same amount.

3.7 OUTPUT PATHWAY INPUTS AND OPTIONS

The **OU**tput pathway contains keywords that define the output options for the model runs. The AERMOD model has three keywords that control different types of tabular output for the main output file of the model, and seven keywords that control separate output file options for specialized purposes. The user may select any combination of output option for a particular application.

3.7.1 Selecting Options for Tabular Printed Outputs.

The three tabular printed output options are controlled by the following keywords:

RECTABLE - Controls output option for high value summary tables by receptor;

MAXTABLE - Controls output option for overall maximum value summary tables; and

DAYTABLE - Controls output option for tables of concurrent values summarized by receptor for each day processed.

The keywords are described in more detail in the order listed above.

The syntax and type for the RECTABLE keyword are summarized below:

Syntax:	OU RECTABLE Aveper FIRST SECOND ... SIXTH or 1ST 2ND ... 6TH
Type:	Optional, Repeatable

where the Aveper parameter is the short term averaging period (e.g. 1, 3, 8 or 24 hr or MONTH) for which the receptor table is selected, and the secondary keywords, FIRST, SECOND, etc., indicate which high values are to be summarized by receptor for that averaging period. The RECTABLE card may be repeated for each averaging period. For cases where the user wants the same RECTABLE options for all short term averaging periods being modeled, the input may be simplified by entering the secondary keyword ALLAVE for the Aveper parameter. The following example will select summaries of the highest, second highest and third highest values by receptor for all averaging periods:

```
OU RECTABLE  ALLAVE  FIRST  SECOND  THIRD
```

The model will also recognize a range of high values on the RECTABLE input card, and therefore the following card will have the effect:

```
OU RECTABLE  ALLAVE  FIRST-THIRD
```

The output file will include tables for only the high values selected. Tables for all source groups for a particular averaging period are grouped together, and the averaging periods are output in the order that they appear the CO AVERTIME card. For each averaging period and source group combination, the tables of high values for the receptor networks (if any) are printed first, followed by any discrete Cartesian receptors, and any discrete polar receptors.

If the CO EVENTFIL keyword has been used to generate an input file for EVENT processing, then the design values identified by the RECTABLE options, e.g., the high-second-high 24-hour average, are included in the events that are defined in the EVENT processing input file.

The syntax and type for the MAXTABLE keyword are summarized below:

Syntax:	`OU MAXTABLE  Aveper  Maxnum`
Type:	`Optional, Repeatable`

where the Aveper parameter is the short term averaging period (e.g. 1, 3, 8 or 24 hr or MONTH) for which the receptor table is selected, and the Maxnum parameter specifies the number of overall maximum values to be summarized for each averaging period. The MAXTABLE card may be repeated for each averaging period. As with the RECTABLE keyword, for cases where the user wants the same MAXTABLE options for all short term averaging periods being modeled, the input may be simplified by entering the secondary keyword ALLAVE for the Aveper parameter. The following example will select the maximum 50 table for all averaging periods:

```
OU MAXTABLE  ALLAVE  50
```

A separate maximum overall value table is produced for each source group. The maximum value tables follow the RECTABLE outputs in the main print file. All source group tables for a particular averaging period are grouped together, and the averaging periods are output in the order that they appear on the CO AVERTIME card.

The syntax and type for the DAYTABLE keyword are summarized below:

Syntax:	`OU DAYTABLE  Avper1  Avper2  Avper3  . . .`
Type:	`Optional, Non-repeatable`

where the Avpern parameters are the short term averaging periods (e.g. 1, 3, 8 or 24 hr or MONTH) for which the daily tables are selected. The DAYTABLE card is non-repeatable, but as with the RECTABLE and MAXTABLE keywords, for cases where the user wants daily tables for all short term averaging periods being modeled, the input may be simplified by entering the

secondary keyword ALLAVE for the first parameter. The following example will select the daily tables for all averaging periods:

```
OU DAYTABLE  ALLAVE
```

For each averaging period for which the DAYTABLE option is selected, the model will print the concurrent averages for all receptors for each day of data processed. The receptor networks (if any) are printed first, followed by any discrete Cartesian receptors, and any discrete polar receptors. Results for each source group are output. For example, if 1, 3, and 24-hour averages are calculated, and the OU DAYTABLE ALLAVE option is used, then for the first day of data processed, there will be 24 sets of tables of hourly averages (one for each hour in the day), eight sets of 3-hour averages (one for each 3-hour period in the day), and one set of 24-hour averages. The averages are printed as they are calculated by the model, but for hours where more than one averaging period is calculated (e.g., hour 24 is the end of an hourly average, a 3-hour average, and a 24-hour average), the order in which the averages are output will follow the order used on the CO AVERTIME card. Note: This option can produce very large output files, especially when used with a full year of data and very short period averages, such 1-hour and 3-hour. It should therefore be used with CAUTION.

3.7.2 Selecting Options for Special Purpose Output Files.

The AERMOD model provides options for seven types of output files for specialized purposes. These options are controlled by the following keywords:

MAXIFILE - Produces file with occurrences of violations of user-specified threshold value;

POSTFILE - Produces file of concurrent (raw) results at each receptor suitable for post-processing;

PLOTFILE - Produces file of design values that can be imported into graphics software for plotting contours;

TOXXFILE - Produces unformatted files of raw results above a threshold value with a special structure for use with the TOXX model component of TOXST;

RANKFILE - Produces file of output values by rank for use in Q-Q (quantile) plots;

EVALFILE - Produces file of output values, including arc-maximum normalized concentrations, suitable for model evaluation studies; and

SEASONHR - Produces file of output values by season and hour-of-day.

The keywords are described in more detail in the order listed above.

The syntax and type for the MAXIFILE keyword are summarized below:

Syntax:	`OU MAXIFILE  Aveper  Grpid  Thresh  Filnam (Funit)`
Type:	`Optional, Repeatable`

where the Aveper parameter is the short term averaging period (e.g. 3, 8, 24 for 3, 8 and 24-hour averages, or MONTH for monthly averages) and Grpid is the source group ID for which the MAXIFILE option is selected. The Thresh parameter is the user-specified threshold value, and Filnam is the name of the file where the MAXIFILE results are to be written. The optional Funit parameter allows the user the option of specifying the Fortran logical file unit for the output file. The user-specified file unit must be in the range of 26-100, inclusive. By specifying the same filename and unit for more than one MAXIFILE card, results for different source groups and/or averaging periods may be combined into a single file. If the Funit parameter is omitted, then the model will dynamically allocate a unique file unit for this file (see Section 3.7.2).

The MAXIFILE card may be repeated for each combination of averaging period and source group, and a different filename should be used for each file. The resulting maximum value file will include several header records identifying the averaging period, source group and the threshold value for that file, and a listing of every occurrence where the result for that averaging period/source group equals or exceeds the threshold value. Each of these records includes the averaging period, source group ID, date for the threshold violation (ending hour of the averaging

period), the x, y, z and flagpole receptor height for the receptor location where the violation occurred, and the concentration value.

Each of the threshold violations, except for monthly averages, identify events that may be modeled for source contribution information with EVENT processing by selecting the CO EVENTFIL option (see Sections 3.2.9 and 3.8). Each of the threshold violations is included as an event on the EV pathway, and is given a name of the form THxxyyyy, where xx is the averaging period, and yyyy is the violation number for that averaging period. For example, an event name of TH240019 identifies the 19th threshold violation for 24-hour averages. Monthly average threshold violations are included in the file specified on the MAXIFILE card, but are not included in the EVENT processing input file since the AERMOD model currently handles only averaging periods of up to 24 hours.

The following examples illustrate the use of the MAXIFILE option:

```
OU MAXIFILE  24  ALL   364.0  MAX24ALL.OUT
OU MAXIFILE  24  PSD    91.0  MAXPSD.OUT    50
OU MAXIFILE   3  PSD   365.0  MAXPSD.OUT    50
OU MAXIFILE   3  PLANT  25.0  C:\OUTPUT\MAXI3HR.FIL
OU MAXIFILE MONTH  ALL  10.0  MAXMONTH.OUT
```

where the 3-hour example illustrates the use of a DOS pathname for the PC, and the last example illustrates the use of monthly averages. The FILNAM parameter may be up to 40 characters in length. It should also be noted that only one MAXIFILE card may be used for each averaging period/source group combination. Note: The MAXIFILE option may produce very large files for runs involving a large number of receptors if a significant percentage of the results exceed the threshold value.

The syntax and type for the POSTFILE keyword are summarized below:

Syntax:	`OU POSTFILE  Aveper  Grpid  Format  Filnam (Funit)`
Type:	`Optional, Repeatable`

where the Aveper parameter is the averaging period (e.g. 3, 8, 24 for 3, 8 and 24-hour averages, MONTH for monthly averages, PERIOD for period averages, or ANNUAL for annual averages) and Grpid is the source group ID for which the POSTFILE option is selected. The Format parameter specifies the format of the POSTFILE output, and may either be the secondary keyword UNFORM for unformatted concentration files, or the secondary keyword PLOT to obtain formatted files of receptor locations (x- and y-coordinates) and concentrations suitable for plotting contours of concurrent values. The Filnam parameter is the name of the file where the POSTFILE results are to be written. The optional Funit parameter allows the user the option of specifying the Fortran logical file unit for the output file. The user-specified file unit must be in the range of 26-100, inclusive. By specifying the same filename and unit for more than one POSTFILE card, results for different source groups and/or averaging periods may be combined into a single file. If the Funit parameter is omitted, then the model will dynamically allocate a unique file unit for this file (see Section 3.8.2).

The POSTFILE card may be repeated for each combination of averaging period and source group, and a different filename should be used for each file. If UNFORM is specified for the Format parameter, then the resulting unformatted file includes a constant-length record for each of the selected averaging periods calculated during the model run. The first variable of each record is an integer variable (4 bytes) containing the ending date (YYMMDDHH) for the averages on that record. The second variable for each record is an integer variable (4 bytes) for the number of hours in the averaging period. The third variable for each record is a character variable of length eight containing the source group ID. The remaining variables of each record contain the calculated average concentration values for all receptors, in the order in which they were defined in the input runstream.

The following examples illustrate the use of the POSTFILE option:

```
OU POSTFILE  24  ALL    UNFORM   PST24ALL.BIN
OU POSTFILE  24  PSD    UNFORM   PST24PSD.BIN
OU POSTFILE   3  PLANT  UNFORM   C:\BINOUT\PST3HR.FIL
OU POSTFILE  MONTH ALL    PLOT   PSTMONTH.PLT
OU POSTFILE PERIOD ALL    PLOT   PSTANN.PLT
```

where the 3-hour example illustrates the use of a DOS pathname for the PC, and the last example illustrates the use of monthly averages. The Filnam parameter may be up to 40 characters in length. The use of separate files for each averaging period/source group combination allows the user flexibility to select only those results that are needed for post-processing for a particular run, and also makes the resulting unformatted files manageable. Note: The POSTFILE option can produce very large files, and should be used with some caution. For a file of hourly values for a full year (8760 records) and 400 receptors, the resulting file will use about 14 megabytes of disk space. To estimate the size of the file (in bytes), use the following equation:

$$\text{File Size (bytes)} = \frac{(\#\text{ of Hrs/Yr})}{(\#\text{ of Hrs/Ave})} * (\#\text{ of Rec} + 4) * 4$$

Divide the result by 1000 to estimate the number of kilobytes (KB) and divide by 1.0E6 to estimate the number of megabytes (MB).

The syntax and type for the PLOTFILE keyword are summarized below:

Syntax:	OU PLOTFILE Aveper Grpid Hivalu Filnam (Funit), or OU PLOTFILE PERIOD Grpid Filnam (Funit) OU PLOTFILE ANNUAL Grpid Filnam (Funit)
Type:	Optional, Repeatable

where the Aveper parameter is the averaging period (e.g. 3, 8, 24 for 3, 8 and 24-hour averages, MONTH for monthly averages, PERIOD for period averages, or ANNUAL for annual averages), Grpid is the source group ID for which the PLOTFILE option is selected, and Hivalu specifies which short term high values are to be output (FIRST for the first highest at each receptor, SECOND for the second highest at each receptor, etc.) Note that the Hivalu parameter is not

specified for PERIOD or ANNUAL averages, since there is only one period or annual average for each receptor. The Filnam parameter is the name of the file where the PLOTFILE results are to be written. The optional Funit parameter allows the user the option of specifying the Fortran logical file unit for the output file. The user-specified file unit must be in the range of 26-100, inclusive. By specifying the same filename and unit for more than one PLOTFILE card, results for different source groups and/or averaging periods may be combined into a single file. If the Funit parameter is omitted, then the model will dynamically allocate a unique file unit for this file (see Section 3.8.2).

The PLOTFILE card may be repeated for each combination of averaging period, source group, and high value, and a different filename should be used for each file. The resulting formatted file includes several records with header information identifying the averaging period, source group and high value number of the results, and then a record for each receptor which contains the x and y coordinates for the receptor location, the appropriate high value at that location, and the averaging period, source group and high value number. The data are written to the file in the order of x-coord, y-coord, concentration so that the file can easily be imported into a graphics package designed to generate contour plots. Many such programs will read the PLOTFILEs directly without any modification, ignoring the header records, and produce the desired plots.

The following examples illustrate the use of the PLOTFILE option:

```
OU PLOTFILE  24  ALL    FIRST  PLT24ALL.FST
OU PLOTFILE  24  ALL    SECOND PLT24ALL.SEC
OU PLOTFILE  24  PSD      2ND  PLTPSD.OUT      75
OU PLOTFILE   3  PSD      2ND  PLTPSD.OUT      75
OU PLOTFILE   3  PLANT    1ST  C:\PLOTS\PLT3HR.FIL
OU PLOTFILE MONTH ALL   THIRD  PLTMONTH.OUT
OU PLOTFILE PERIOD ALL         PSTANN.PLT
```

where the 3-hour example illustrates the use of a DOS pathname for the PC, and the last example illustrates the use of monthly averages. As illustrated by the second and third examples, the high

value parameter may also be input as secondary keywords using the standard abbreviations of 1ST, 2ND, 3RD, . . . 10TH. The Filnam parameter may be up to 40 characters in length. The use of separate files for each averaging period, source group, high value combination allows the user flexibility to select only those results that are needed for plotting from a particular run.

The syntax and type for the TOXXFILE keyword are summarized below:

Syntax:	`OU TOXXFILE  Aveper  Cutoff  Filnam  (Funit)`
Type:	`Optional, Repeatable`

where the Aveper parameter is the short term averaging period (e.g. 1, 3, 8, 24 for 1, 3, 8 and 24-hour averages, or MONTH for monthly averages) for which the TOXXFILE option has been selected. The Cutoff (threshold) parameter is the user-specified threshold cutoff value in g/m^3, and Filnam is the name of the file where the TOXXFILE results are to be written. It is important to note that the units of the Cutoff parameter are g/m^3, regardless of the input and output units selected with the SO EMISUNIT card. The optional Funit parameter allows the user the option of specifying the Fortran logical file unit for the output file. The user-specified file unit must be in the range of 26-100, inclusive. If the Funit parameter is omitted, then the model will dynamically allocate a unique file unit for this file (see Section 3.8.2). While the TOXXFILE option may be specified for any of the short term averaging periods that are identified on the CO AVERTIME card for a particular run, a non-fatal warning message will be generated if other than 1-hour averages are specified. This is because the TOXST model currently supports only 1-hour averages.

The TOXXFILE card may be repeated for each averaging period, but a different filename should be used for each file since the structure of the output file generated by the TOXXFILE option does not allow for a clear way to distinguish between results for different averaging periods. The resulting output file for the AERMOD model is an unformatted file with several header records identifying the title, averaging period, receptor information, and the threshold value for that file, followed by records listing every occurrence where the result for any source group for that averaging period equals or exceeds the threshold value. When one of the source

groups exceeds the threshold value, the results for all source groups for that averaging period and receptor location are output. Each concentration that is output through the TOXXFILE option is paired with an integer ID variable that identifies the averaging period (hour number of the year), the source group number, and the receptor number corresponding to that value. The concentration values and corresponding ID variables are stored in buffer arrays, and the arrays are then written to the unformatted output file when full. The size of the arrays is controlled by the NPAIR PARAMETER defined in MODULE MAIN1, and is initially set at 100. At the end of the modeling run, any values remaining in the buffer arrays are written to the file, padded to the right with zeroes. The structure of the output file generated by the TOXXFILE option is described in more detail in Section 3.8.2 and in Appendix D. When using the TOXXFILE option, the user will normally place a single source in each source group. The user should refer to the user's guide for TOXST for further instructions on the application of the TOXXFILE option of the AERMOD model.

The following examples illustrate the use of the TOXXFILE option:

```
OU TOXXFILE   1  1.0E-5   TOXX1HR.BIN
OU TOXXFILE  24  2.5E-3   TOXX24HR.BIN    50
```

The Filnam parameter may be up to 40 characters in length. It should be noted that only one TOXXFILE card may be used for each averaging period. Note: The TOXXFILE option may produce very large files for runs involving a large number of receptors if a significant percentage of the results exceed the threshold value.

The RANKFILE keyword outputs values by rank for use in Q-Q (quantile) plots. The MAXTABLE option must be specified first in order to use the RANKFILE option for a particular averaging period. However, the RANKFILE output differs from the results in the MAXTABLE output in that duplicate date/hour occurrences are removed. The syntax and type for the RANKFILE keyword are summarized below:

Syntax:	`OU RANKFILE  Aveper  Hinum  Filnam  (Funit)`
Type:	`Optional, Repeatable`

where the Aveper parameter is the averaging period (e.g., 3, 8, 24 for 3, 8, and 24-hour averages, or MONTH for monthly averages), and Hinum is the number of high values to be ranked. The RANKFILE keyword cannot be used with PERIOD averages. As noted above, the MAXTABLE option must be specified first for the particular Aveper, and the Hinum parameter on the RANKFILE card must be less than or equal to the Maxnum parameter on the corresponding MAXTABLE card. Since duplicate dates are removed from the RANKFILE output, the output file may contain less than the number of requested high values. The NMAX parameter, which controls the maximum number of values that can be stored, has been set initially to 400. The Filnam parameter is the name of the file (up to 40 characters) where the RANKFILE results are to be written. The optional Funit parameter allows the user the option of specifying the Fortran logical file unit for the output file. The user-specified file unit must be in the range of 26-100, inclusive. By specifying the same filename and unit for more than one RANKFILE card, results for different averaging periods may be combined into a single file. If the Funit parameter is omitted, the model will dynamically allocate a unique file unit for this file according to the following formula:

$$IRKUNT = 100 + IAVE$$

where IRKUNT is the Fortran unit number and IAVE is the averaging period number (the order of the averaging period as specified on the CO AVERTIME card).

The EVALFILE option is specifically designed for use in generating residuals for model evaluation studies. The EVALFILE output consists of the arc-maximum normalized concentration values for each hour of meteorology and for each source specified. The arc groupings of the receptors must be specified using the RE EVALCART keyword described above. The syntax and type for the EVALFILE keyword are summarized below:

Syntax:	`OU EVALFILE  Srcid  Filnam  (Funit)`
Type:	`Optional, Repeatable`

where the Srcid parameter is the source ID for which EVALFILE results are requested, the Filnam parameter is the name of the file (up to 40 characters) where the EVALFILE results are to be written, and the optional Funit parameter allows the user the option of specifying the Fortran logical file unit for the output file. The user-specified file unit must be in the range of 26-100, inclusive. By specifying the same filename and unit for more than one EVALFILE card, results for different sources may be combined into a single file. If the Funit parameter is omitted, the model will dynamically allocate a unique file unit for this file according to the following formula:

$$IELUNT = 400 + ISRC*5$$

where IELUNT is the Fortran unit number and ISRC is the source number (the order of the source as specified on the SO pathway).

For each hour of meteorological data processed and for each receptor grouping (e.g., arc), the EVALFILE option outputs five records containing the source ID, date, arc ID, arc-maximum normalized concentration (χ/Q), emission rate, and other plume dispersion and meteorological variables associated with the arc-maximum. Since the EVALFILE option looks at receptor groupings, it must be used in conjunction with the EVALCART keyword described above for the RE pathway, and a fatal error is generated if no receptor groups are identified.

The SEASONHR option is used to output a file containing the average results by season and hour-of-day. To select this option, the user must include the SEASONHR keyword on the OU pathway. The syntax, type, and order for the SEASONHR keyword are summarized below:

Syntax:	`OU SEASONHR  GroupID  Filenam  (FUnit)`
Type:	`Optional, Repeatable`

where the GroupID parameter specifies the source group to be output, FileName specifies the name of the output file, and the optional FileUnit parameter specifies an optional file unit and must be in the range 26-100, inclusive. If FileUnit is left blank, then the model will dynamically assign a file unit based on the formula 302+IGRP*10, where IGRP is the group index number. A sample from a SEASONHR output file is shown below:

```
* AERMOD (02222):  Example of SEASONHR Output File Option
* MODELING OPTIONS USED:
*  CONC                 WDEP   RURAL  FLAT          TOXICS
*         FILE OF SEASON/HOUR VALUES FOR SOURCE GROUP: ALL
*         FOR A TOTAL OF   216 RECEPTORS.
*         FORMAT: (4(1X,F13.5),1X,F8.2,2X,A8,2X,I4,2X,I4,2X,I4,2X,A8)
*        X             Y      AVERAGE CONC   ZELEV     GRP     NHRS  SEAS  HOUR  NET ID
*   ___________   ___________   ___________   ______  ________  ____  ____  ____ ________
       8.68241      49.24039       0.00000     0.00  ALL         87     1     1  POL1
      17.36482      98.48077       0.00000     0.00  ALL         87     1     1  POL1
      86.82409     492.40387       0.18098     0.00  ALL         87     1     1  POL1
     173.64818     984.80774       2.52520     0.00  ALL         87     1     1  POL1
     868.24091    4924.03857       2.07470     0.00  ALL         87     1     1  POL1
    1736.48181    9848.07715       0.93252     0.00  ALL         87     1     1  POL1
      17.10101      46.98463       0.00000     0.00  ALL         87     1     1  POL1
      34.20201      93.96926       0.00000     0.00  ALL         87     1     1  POL1
     171.01007     469.84631       0.15772     0.00  ALL         87     1     1  POL1
     342.02014     939.69263       2.48554     0.00  ALL         87     1     1  POL1
    1710.10071    4698.46289       6.09119     0.00  ALL         87     1     1  POL1
    3420.20142    9396.92578       4.49830     0.00  ALL         87     1     1  POL1
      25.00000      43.30127       0.00000     0.00  ALL         87     1     1  POL1
      50.00000      86.60254       0.00000     0.00  ALL         87     1     1  POL1
     250.00000     433.01270       0.10114     0.00  ALL         87     1     1  POL1
     500.00000     866.02539       2.12970     0.00  ALL         87     1     1  POL1
    2500.00000    4330.12695       2.79993     0.00  ALL         87     1     1  POL1
    5000.00000    8660.25391       1.97200     0.00  ALL         87     1     1  POL1
```

The NHRS column in the output file contains the number of non-calm and non-missing hours used to calculate the season-by-hour-of-day averages. The SEAS column is the season index, and is 1 for winter, 2 for spring, 3 for summer and 4 for fall. The records loop through hour-of-day first, and then through the seasons.

3.7.3 EVENT Processing Options

EVENT processing in the AERMOD model is designed specifically to perform source contribution analyses for short term average (less than or equal to 24-hour) events. The events may either be generated by the AERMOD model, or they may be user-specified events, or both. Because of this rather narrow focus of applications, the output options are limited to a single keyword. The EVENTOUT keyword controls the level of detail in the source contribution output from the EVENT model. The syntax and type of the EVENTOUT keyword are summarized below:

Syntax:	`OU EVENTOUT SOCONT DETAIL`
Type:	`Mandatory, Non-repeatable`

where the SOCONT secondary keyword specifies the option to produce only the source contribution information in the output file, and the DETAIL secondary keyword specifies the option to produce more detailed summaries in the output file. The SOCONT option provides the average concentration (or total deposition) value (i.e., the contribution) from each source for the period corresponding to the event for the source group. The basic source contribution information is also provided with the DETAIL option. In addition, the DETAIL option provides the hourly average concentration (or total deposition) values for each source for every hour in the averaging period, and a summary of the hourly meteorological data for the event period. In general, the DETAIL option produces a larger output file than the SOCONT file, especially if there are a large number of sources. There is no default setting for the EVENTOUT options.

3.8 CONTROLLING INPUT AND OUTPUT FILES

This section describes the various input and output files used by the AERMOD model, and discusses control of input and output (I/O) on the IBM-compatible PC environment. Much of this discussion also applies to operating the model in other environments.

3.8.1 Description of AERMOD Input Files

The two basic types of input files needed to run all of the AERMOD model are the input runstream file containing the modeling options, source data and receptor data, and the two input meteorological data files. Each of these is discussed below, as well as a special file that may be used to initialize the AERMOD model with intermediate results from a previous run.

3.8.1.1 Input Runstream File.

The input runstream file contains the user-specified options for running the various AERMOD model (called AERMOD.INP), includes the source parameter data and source group information, defines the receptor locations, specifies the location and parameters regarding the meteorological data, and specifies the output options. Details regarding the keywords and parameters used in the input runstream file are provided in Section 3, and Appendix B.

For the PC-executable version of the model available on the SCRAM website, the runstream file is explicitly opened by the model using a Fortran OPEN statement, and the integer variable, INUNIT, specifies the unit number for the file. The variable INUNIT is initialized to a value of 7 in a DATA statement in MODULE MAIN1, and is therefore available to all of the necessary subroutines.

3.8.1.2 Meteorological Data Files.

The input meteorological data is read into the AERMOD model from two separate data files, one corresponding to surface (scalar) parameters, and the other corresponding to multi-level profiles of data. The meteorological data filenames and format are specified within the input runstream file using the ME SURFFILE and PROFFILE keywords. The AERMOD model accepts meteorological data that has been preprocessed by the AERMET meteorological preprocessor program (EPA, 2004b). The data are read from formatted ASCII files of hourly sequential records.

The meteorological data files are explicitly opened by the model using Fortran OPEN statements, and the integer variables MFUNIT for the surface/scalar file and MPUNIT for the profile file are used to specify the unit numbers for the files. The variable MFUNIT is initialized to a value of 19 and MPUNIT is initialized to a value of 16 in a DATA statement in MODULE MAIN1, and are therefore available to all of the necessary subroutines.

3.8.1.3 Initialization File for Model Re-start.

The AERMOD model has an optional capability to store intermediate results to an unformatted (sometimes called binary) file for later re-starting of the model in the event of a power failure or user interrupt. This unformatted file may therefore be used as an input file to initialize the model. This option is controlled by the SAVEFILE (saves intermediate results to a file) and the INITFILE (initialize result arrays from a previously saved file) keywords on the CO pathway.

When initializing the model for the re-start option, the user specifies the name of the unformatted results file on the INITFILE keyword. The default filename used if no parameter is provided is TMP.FIL. The initialization file is explicitly opened by the AERMOD model, and the integer variable, IRSUNT, specifies the unit number for the file. The variable IRSUNT is initialized to a value of 15 in a DATA statement in MODULE MAIN1, and is therefore available to all of the necessary subroutines.

3.8.2 Description of AERMOD Output Files

The AERMOD model produce a variety of output files, including the main print file of model results, an unformatted file of intermediate results for later re-start of the model (AERMOD only), and several output data files for specialized purposes. These files are described in detail below.

3.8.2.1 Output Print File.

The AERMOD model produces a main output print file of model results called AERMOD.OUT. The contents and organization of this file were shown in Figure 2-5. This file includes an echo of the input runstream images at the beginning of the file (up until a NO ECHO input is encountered). A summary of runstream setup messages and a summary of the inputs follow the echo of inputs. The input summary includes a summary of modeling options, source data, receptor data, and meteorological data, following the same order as the pathways in the runstream file. If model calculations are performed, then the model results are summarized next. The content and order of the model result summaries depend on the output options selected and on the particular model being run. Following the detailed model results are summary tables of the high values for each averaging period and source group. The final portion of the main output print file is the summary of messages for the complete model run.

For the PC-executable version of the model available on the SCRAM website, the main print output file is explicitly opened by the model using a Fortran OPEN statement, and the integer variable, IOUNIT, specifies the unit number for the file. The variable IOUNIT is initialized to a value of 8 in a DATA statement in MODULE MAIN1, and is therefore available to all of the necessary subroutines.

By opening the printed output file explicitly, the outputs are not automatically formatted for the printer. This formatting is accomplished using the CARRIAGECONTROL specifier in the OPEN statement for the output file.

3.8.2.2 Detailed Error Message File.

The user may select an option for the model to save a separate file of detailed error and other messages, through use of the CO ERRORFIL keyword. The format and syntax of these messages is described in Appendix C. The order of messages within the file is the order in which they were generated by the model. The file includes all types of messages that were generated.

The error message file is explicitly opened by the model using a Fortran OPEN statement, and the integer variable, IERUNT, specifies the unit number for the file. The variable IERUNT is initialized to a value of 10 in a DATA statement in MODULE MAIN1, and is therefore available to all of the necessary subroutines.

3.8.2.3 Intermediate Results File for Model Re-start.

The AERMOD model has an optional capability to store intermediate results to an unformatted (sometimes called binary) file for later re-starting of the model in the event of a power failure or user interrupt. This unformatted file may therefore be used as an input file to initialize the model. This option is controlled by the SAVEFILE (saves intermediate results to a file) and the INITFILE (initialize result arrays from a previously saved file) keywords on the CO pathway.

When saving the intermediate results for the re-start option, the user specifies the name of the unformatted results file on the SAVEFILE keyword. The user has the option of specifying a single filename, two filenames (for alternate saves), or specifying no filename. The default filename used if no parameter is provided is TMP.FIL. If a single file is used, then the intermediate results file is overwritten on each successive dump, with the chance that the file will be lost if the interrupt occurs during the time that the file is opened. If two filenames are provided, then the model also saves to the second file on alternate dumps, so that the next most recent dump will always be available. The main save file is explicitly opened by the AERMOD model, and the integer variable, IDPUNT, specifies the unit number for the file. The variable IDPUNT is initialized to a value of 12 in a BLOCK DATA subprogram of the model. If a second save file is used, then it is also opened explicitly, and the integer variable IDPUN2, initialized to a value of 14, specifies the unit number.

3.8.2.4 Maximum Value/Threshold File.

The user may select an option for the AERMOD model to generate a file or files of concentration values exceeding a user-specified threshold. The OU MAXIFILE keyword controls this option. The user may select separate files for each averaging period and source group combination for which a list of threshold violations may be needed. Each file includes several records with header information identifying the averaging period, source group and threshold value, and then a record for every occurrence where the result for that averaging period/source group equals or exceeds the threshold value. Each of these records includes the averaging period, source group ID, date for the threshold violation (ending hour of the averaging period), the x, y, z and flagpole receptor height for the receptor location where the violation occurred, and the concentration value.

The structure of the threshold violation file is described in more detail in Appendix D. Each of the files selected by the user is opened explicitly by the model as an formatted file. The filenames are provided on the input runstream image. The user may specify the file unit on the MAXIFILE card through the optional FUNIT parameter. User-specified units must be greater than or equal to 26, and are recommended to be less than or equal to 100. If no file unit is specified, then the file unit is determined internally according to the following formula:

$$IMXUNT = 100 + IGRP*10 + IAVE$$

where IMXUNT is the Fortran unit number, IGRP is the source group number (the order in which the group is defined in the runstream file), and IAVE is the averaging period number (the order of the averaging period as specified on the CO AVERTIME card). This formula will not cause any conflict with other file units used by the model for up to 9 source groups and up to 9 short term averaging periods.

3.8.2.5 Sequential Results File for Postprocessing.

The user may select an option for the AERMOD model to generate a file or files of

concentration values suitable for postprocessing. The OU POSTFILE keyword controls this option. The user may select separate files for each averaging period and source group combination for which postprocessing may be needed. For each file requested, the user has the option of specifying whether to use unformatted files suitable for postprocessing or to use a plot format which could allow for importing the x,y,conc files into a graphics package for plotting. For the unformatted file option, each file consists of sequential unformatted records of values at each receptor location for every averaging period calculated. For the plot file format option, each file consists of formatted records listing the x-coordinate, y-coordinate and concurrent concentration values for each receptor and for all averaging periods calculated. For certain applications, these files may become quite large, and should only be used when needed, especially when using the plot format.

The structure of both types of postprocessing file is described in more detail in Appendix D. Each of the postprocessing files selected by the user is opened explicitly by the model as either an unformatted or a formatted file, depending on the option selected. The filenames are provided on the input runstream image. The user may specify the file unit on the POSTFILE card through the optional FUNIT parameter. User-specified units must be greater than or equal to 26, and are recommended to be less than or equal to 100. If no file unit is specified, then the file unit is determined internally according to the following formulas:

IPSUNT = 200 + IGRP*10 + IAVE for short term averages

IAPUNT = 300 + IGRP*10 - 5 for PERIOD averages

where IPSUNT and IAPUNT are the Fortran unit numbers, IGRP is the source group number (the order in which the group is defined in the runstream file), and IAVE is the averaging period number (the order of the averaging period as specified on the CO AVERTIME card). This formula will not cause any conflict with other file units used by the model for up to 9 source groups and up to 9 short term averaging periods.

3.8.2.6 High Value Summary File for Plotting.

The user may select an option for the AERMOD model to generate a file or files of the highest concentration values at each receptor suitable for importing into a graphics package in order to generate contour plots. The OU PLOTFILE keyword controls this option. The user may select separate files for each averaging period, source group and high value combination for which a plot file may be needed. Each file includes several records with header information identifying the averaging period, source group and high value number of the results, and then a record for each receptor which contains the x and y coordinates for the receptor location, the appropriate high value at that location, and the averaging period, source group and high value number.

The structure of the plot file is described in more detail in Appendix D. Each of the plot files selected by the user is opened explicitly by the model as an formatted file. The filenames are provided on the input runstream image. The user may specify the file unit on the PLOTFILE card through the optional FUNIT parameter. User-specified units must be greater than or equal to 26, and are recommended to be less than or equal to 100. If no file unit is specified, then the file unit is determined internally according to the following formulas:

IPLUNT = (IVAL+3)*100 + IGRP*10 + IAVE for short term averages
IPPUNT = 300 + IGRP*10 for PERIOD averages

where IPLUNT and IPPUNT are the Fortran unit numbers, IVAL is the high value number (1 for FIRST highest, 2 for SECOND highest, etc.), IGRP is the source group number (the order in which the group is defined in the runstream file), and IAVE is the averaging period number (the order of the averaging period as specified on the CO AVERTIME card). This formula will not cause any conflict with other file units used by the model for up to 9 source groups and up to 9 short term averaging periods.

3.8.2.7 TOXX Model Input Files

The user may select an option for the AERMOD model to generate an unformatted file or files of concentration values exceeding a user-specified threshold for use with the TOXX model component of TOXST. The OU TOXXFILE keyword controls this option. The user may select separate files for each averaging period for which a threshold violation file may be needed. Each file includes several records with header information identifying the title, averaging period, threshold value, and receptor network information, and then records including every occurrence where the result of any source group for that averaging period equals or exceeds the threshold value. Records are also output that identify the averaging period (hour number of the year), source group number and receptor number corresponding to the concentration values.

The structure of the threshold exceedance file for use with the TOXX model component of TOXST is described in more detail in Appendix D. Each of the files selected by the user is opened explicitly by the model as an unformatted file. The filenames are provided on the input runstream image. The user may specify the file unit on the TOXXFILE card through the optional Funit parameter. User-specified units must be greater than or equal to 26, and are recommended to be less than or equal to 100. If no file unit is specified, then the file unit is determined internally according to the following formula:

$$ITXUNT = 300 + IAVE$$

where ITXUNT is the Fortran unit number, and IAVE is the averaging period number (the order of the averaging period as specified on the CO AVERTIME card). This formula will not cause any conflict with other file units used by the model for up to 4 short term averaging periods.

The user may also select an option for the AERMOD model to generate an output for use with the RISK model component of TOXLT. The OU TOXXFILE keyword also controls this option. The user can specify a separate TOXXFILE for each long term averaging period and source group combination. The TOXXFILE option may also be used for PERIOD averages with

the AERMOD model. The structure of the TOXXFILE output for AERMOD is very similar to the long term PLOTFILE output, except that results are output for each individual source in the specified source group. The structure of the long term TOXXFILE is described in more detail in Appendix D. Each of the files selected by the user is opened explicitly by the model as a formatted file. The filenames are provided on the input runstream image. The user may specify the file unit on the TOXXFILE card through the optional Funit parameter. User-specified units must be greater than or equal to 26, and are recommended to be less than or equal to 100. If no file unit is specified, then the file unit is determined internally according to the following formulas:

ITXUNT = 500 + IAVE*10 + IGRP for long term averages
IPXUNT = 700 + IGRP*10 for PERIOD averages

where ITXUNT and IPXUNT are the Fortran unit numbers, IAVE is the averaging period number (in the order of months, seasons or quarters, and annual), and IGRP is the source group number (in the order is which the groups are defined in the SO pathway). This formula will not cause any conflict with other file units used by the model for up to 9 source groups.

3.8.3 Control of File Inputs and Outputs (I/O)

3.8.3.1 Control of I/O on PCs.

The main input runstream file and the main output print file are specified internally by AERMOD as AERMOD.INP and AERMOD.OUT, respectively. Therefore, a standard command line to execute the AERMOD model might look something like this:

```
C:\>AERMOD
```

where the "DOS prompt" has been given as "C:\>", but may look different on different systems, or may include a subdirectory specification. The output file generated by the DOS version

includes page feeds that are written directly to the file as part of the header for each page, rather than using the Fortran carriage control of '1'. This is accomplished by including a compiler-specific parameter to set CARRIAGECONTROL = ‘Fortran’ on the OPEN statement for the output file.

3.8.3.2 Controlling I/O on Other Computer Systems.

Since the main input runstream file and the main output print file are specified internally by AERMOD, control of I/O on other computer systems will be the same, with the possible exception of the compiler-specific option to set CARRIAGECONTROL = ‘Fortran’ on the OPEN statement for the output file.

4.0 REFERENCES

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APPENDIX A. ALPHABETICAL KEYWORD REFERENCE

This appendix provides an alphabetical listing of all of the keywords used by the AERMOD model. Each keyword is identified as to the pathway for which it applies, the keyword type (either mandatory or optional, and either repeatable or non-repeatable), and with a brief description of the function of the keyword. For a more complete description of the keywords, including a list of associated parameters, refer to the Detailed Keyword Reference in Section 3 or the Functional Keyword/Parameter Reference in Appendix B.

Keyword	Path	Type	Keyword Description
AREAVERT	SO	M - R	Specifies location of vertices for an AREAPOLY source type (mandatory if AREAPOLY source is used)
AVERTIME	CO	M - N	Averaging time(s) to process (up to NAVE short term plus PERIOD or ANNUAL averages)
BUILDHGT	SO	O - R	Building height values for each wind sector
BUILDWID	SO	O - R	Building width values for each wind sector
DAYRANGE	ME	O - R	Specifies days or ranges of days to process (default is to process all data read in)
DAYTABLE	OU	O - N	Option to provide summaries for each averaging period for each day processed.
DCAYCOEF	CO	O - N	Optional decay coefficient for exponential decay
DEBUGOPT	CO	O - N	Option to generate detailed result and meteorology files for debugging purposes
DISCCART	RE	O - R	Defines the discretely placed receptor locations referenced to a Cartesian system
DISCPOLR	RE	O - R	Defines the discretely placed receptor locations referenced to a polar system
ELEVUNIT	SO RE	O - N O - N	Defines input units for receptor elevations (RE path), or source elevations (SO path) (defaults to meters)
EMISFACT	SO	O - R	Optional input for variable emission rate factors
EMISUNIT	SO	O - N	Optional conversion factors for emission units and concentration units

Type: M - Mandatory N - Non-repeatable
O - Optional R - Repeatable

Keyword	Path	Type	Keyword Description
ERRORFIL	CO	O - N	Option to generate detailed error listing file (error file is mandatory for CO RUNORNOT NOT case)
EVALCART	RE	O - R	Defines discretely placed receptor locations referenced to a Cartesian system, grouped by arc for use with the EVALFILE output option
EVALFILE	OU	O - R	Option to output file of normalized arc maxima for model evaluation studies
EVENTFIL	CO	O - N	Specifies whether to generate an input file for EVENT model
EVENTLOC	EV	M - R	Describes receptor location for an event
EVENTOUT	OU	M - N	Specifies the level of output information provided by the EVENT model
EVENTPER	EV	M - R	Describes data and averaging period for an event
FINISHED	ALL	M - N	Identifies the end of inputs for a particular pathway
FLAGPOLE	CO	O - N	Specifies whether to accept receptor heights above local terrain (m) for use with flagpole receptors, and allows for a default flagpole height to be specified
GRIDCART	RE	O - R	Defines a Cartesian grid receptor network
GRIDPOLR	RE	O - R	Defines a polar receptor network
HALFLIFE	CO	O - N	Optional half life used for exponential decay
HOUREMIS	SO	O - R	Option for specifying hourly emission rates in a separate file
INCLUDED	SO, RE	O - R	Option to include input data from a separate file in the runstream for the SO and/or RE pathways
INITFILE	CO	O - N	Option to initialize model from file of intermediate results generated by SAVEFILE option
LOCATION	SO	M - R	Identifies coordinates for particular source location

Keyword	Path	Type	Keyword Description
MAXIFILE	OU	O - R	Option to list events exceeding a threshold value to file (if CO EVENTFIL option is used, these events are included in the input file generated for the EVENT model)
MAXTABLE	OU	O - R	Option to summarize the overall maximum values
MODELOPT	CO	M - N	Job control and dispersion options
MULTYEAR	CO	O - N	Specifies that run is part of a multi-year run, e.g., for PM-10 H6H in five years
PLOTFILE	OU	O - R	Option to write certain results to a storage file suitable for input to plotting routines
POLLUTID	CO	M - N	Identifies pollutant being modeled
POSTFILE	OU	O - R	Option to write results to a mass storage file for postprocessing
PROFBASE	ME	M - N	Specifies the base elevation (above MSL) for the potential temperature profile
PROFFILE	ME	M - N	Describes input profile meteorological data file
RANKFILE	OU	O - R	Option to produce output file of ranked values for Q-Q plots

Keyword	Path	Type	Keyword Description
RECTABLE	OU	O - R	Option to output value(s) by receptor
RUNORNOT	CO	M - N	Identifies whether to run model or process setup information only
SAVEFILE	CO	O - N	Option to store intermediate results for later restart of the model after user or system interrupt
SCIMBYHR	ME	O - N	Specifies sampling parameters for the SCIM option
SITEDATA	ME	O - N	Describes on-site meteorological station
SRCGROUP	SO	M - R	Identification of source groups
SRCPARAM	SO	M - R	Identifies source parameters for a particular source
STARTEND	ME	O - N	Specifies start and end dates to be read from input meteorological data file (default is to read entire file)
STARTING	ALL	M - N	Identifies the start of inputs for a particular pathway
SURFDATA	ME	M - N	Surface meteorological station
SURFFILE	ME	M - N	Describes input surface meteorological data file
TITLEONE	CO	M - N	First line of title for output
TITLETWO	CO	O - N	Optional second line of output title
TOXXFILE	OU	O - R	Creates output file formatted for use with TOXX model component of TOXST
UAIRDATA	ME	M - N	Upper air meteorological station
WDROTATE	ME	O - N	Wind direction rotation adjustment
WINDCATS	ME	O - N	Upper bound of wind speed categories

APPENDIX B. FUNCTIONAL KEYWORD/PARAMETER REFERENCE

This appendix provides a functional reference for the keywords and parameters used by the input runstream files for the AERMOD model. The keywords are organized by functional pathway, and within each pathway the order of the keywords is based on the function of the keyword within the model. The pathways used by the model are as follows, in the order in which they appear in the runstream file and in the tables that follow:

CO - for specifying overall job **CO**ntrol options;
SO - for specifying **SO**urce information;
RE - for specifying **RE**ceptor information;
ME - for specifying **ME**teorology information and options;
EV - for specifying **EV**ent information and options;
OU - for specifying **OU**tput options.

The pathways and keywords are presented in the same order as in the Detailed Keyword Reference in Section 3, and in the Quick Reference at the end of the manual.

Two types of tables are provided for each pathway. The first table lists all of the keywords for that pathway, identifies each keyword as to its type (either mandatory or optional and either repeatable or non-repeatable), and provides a brief description of the function of the keyword. The second type of table, which takes up more than one page for most pathways, presents the parameters for each keyword, in the order in which they should appear in the runstream file where order is important, and describes each parameter in detail.

The following convention is used for identifying the different types of input parameters. Parameters corresponding to secondary keywords which should be input "as is" are listed on the tables with all capital letters and are underlined. Other parameter names are given with an initial capital letter and are not input "as is." In all cases, the parameter names are intended to be descriptive of the input variable being represented, and they often correspond to the Fortran variable names used in the model code. Parentheses around a parameter indicate that the parameter is optional for that keyword. The default that is taken when an optional parameter is left blank is explained in the discussion for that parameter.

TABLE B-1
DESCRIPTION OF CONTROL PATHWAY KEYWORDS

CO Keywords	Type	Keyword Description
STARTING	M - N	Identifies the start of CONTROL pathway inputs
TITLEONE	M - N	First line of title for output
TITLETWO	O - N	Optional second line of title for output
MODELOPT	M - N	Job control and dispersion options
AVERTIME	M - N	Averaging time(s) to process
URBANOPT	O - N	Specifies parameters for urban dispersion option
POLLUTID	M - N	Identifies type of pollutant being modeled
HALFLIFE	O - N[1]	Optional half life used for exponential decay
DCAYCOEF	O - N[1]	Optional decay coefficient
FLAGPOLE	O - N	Specifies whether to accept receptor heights above local terrain (m) for use with flagpole receptors, and allows for default flagpole height to be specified
RUNORNOT	M - N	Identifies whether to run model or process setup information only
EVENTFIL[2]	O - N	Specifies whether to generate an input file for EVENT model
SAVEFILE[3]	O - N	Option to store intermediate results for later restart of the model after user or system interrupt
INITFILE[3]	O - N	Option to initialize model from file of intermediate results generated by SAVEFILE option
MULTYEAR[3]	O - N	Option to process multiple years of meteorological data (one year per run) and accumulate high short term values across years
DEBUGOPT	O - N	Option to generate detailed result and meteorology files for debugging purposes
ERRORFIL	O - N	Option to generate detailed error listing file
FINISHED	M - N	Identifies the end of CONTROL pathway inputs

Type: M - Mandatory N - Non-Repeatable
O - Optional R - Repeatable

1) Either HALFLIFE or DCAYCOEF may be specified. If both cards appear a warning message will be issued and the first value entered will be used in calculations. Default assumes a half life of 4 hours for SO_2 modeled in urban mode.

2) The EVENTFIL keyword controls whether or not to generate an input file for EVENT processing. The primary difference between AERMOD regular processing and EVENT processing by AERMOD is in the treatment of source group contributions. The AERMOD model treats the source groups independently, whereas EVENT processing determines individual source contributions to particular events, such as the design concentrations determined from AERMOD, or user-specified events. By specifying the EVENTFIL keyword, an input runstream file will be generated that can be used directly for EVENT processing. The events included in the generated EVENT processing input file are defined by the RECTABLE and MAXIFILE keywords on the OU pathway, and are placed in the EVent pathway.

3) The SAVEFILE and INITFILE keywords work together to implement the model's re-start capabilities. Since the MULTYEAR option utilizes the re-start features in a special way to accumulate high short term values from year to year, it cannot be used together with the SAVEFILE or INITFILE keyword in the same model run.

TABLE B-2

DESCRIPTION OF CONTROL PATHWAY KEYWORDS AND PARAMETERS

Keyword	Parameters	
TITLEONE	Title1	
where:	Title1	First line of title for output, character string of up to 68 characters
TITLETWO	Title2	
where:	Title2	Optional second line of title for output, character string of up to 68 characters
MODELOPT	DFAULT CONC FLAT NOSTD NOCHKD NOWARN SCREEN TOXICS SCIM	
where:	DFAULT	Specifies use of regulatory default options (stack tip downwash, elevated terrain effects), overrides the presence of FLAT, NOSTD, NOCHKD, and SCREEN keywords
	CONC	Specifies calculation of concentration values (deposition algorithm has not been implemented yet)
	FLAT	Option to assume flat terrain
	NOSTD	Option to use no stack-tip downwash
	NOCHKD	Option to by-pass date checking for non-sequential meteorological data file (for evaluation and screening purposes only)
	NOWARN	Option to suppress printing of warning messages in the main output file
	SCREEN	Option to run AERMOD in a screening mode (makes centerline calculations, sets NOCHKD option on, limits averaging period to 1-hour)
	TOXICS	Option to use air toxics option(s): SCIM
	SCIM	Sampled Chronological Input Model; parameters must be specified on the ME pathway
AVERTIME	Time1 Time2 Time3 Time4 MONTH PERIOD	
where:	TimeN	Nth optional averaging time (1, 2, 3, 4, 6, 8, 12, 24-hr; number of periods limited by NAVE parameter)
	MONTH	Option to calculate MONTHly averages (counts toward NAVE limit)
	PERIOD	Option to calculate averages for the entire data PERIOD

TABLE B-2 (CONT.)

DESCRIPTION OF CONTROL PATHWAY KEYWORDS AND PARAMETERS

URBANOPT	Urbpop (Urbname) (UrbRoughness)	
where:	UrbPop UrbName UrbRoughness	Specifies the population of the urban area Specifies the name of the urban area (optional) Specifies the urban surface roughness length, meters (optional, defaults to 1.0m)
POLLUTID	Pollut	
where:	Pollut	Identifies type of pollutant being modeled. Any name of up to eight characters may be used, e.g., SO2, NOX, CO, PM10, TSP or OTHER. Use of PM10, PM-10 or OTHER allows for the use of the MULTYEAR option.
HALFLIFE	Haflif	
where:	Haflif	Half life used for exponential decay (s)
DCAYCOEF	Decay	
where:	Decay	Decay coefficient for exponential decay (s^{-1}) = 0.693/HAFLIF
FLAGPOLE	(Flagdf)	
where:	Flagdf	Default value for height of (flagpole) receptors above local ground level, a default value of 0.0 m is used if this optional parameter is omitted

TABLE B-2 (CONT.)

DESCRIPTION OF CONTROL PATHWAY KEYWORDS AND PARAMETERS

RUNORNOT	RUN or NOT	
where:	RUN NOT	Indicates to run full model calculations Indicates to process setup data and report errors, but to not run full model calculations
EVENTFIL	(Evfile) (Evopt)	
where:	Evfile Evopt	Identifies the filename to be used to generate a file for input to EVENT model (Default=EVENTFIL.INP) Optional parameter to specify the level of output detail selected for the EVENT model: either SOCONT or DETAIL (default is DETAIL if this parameter is omitted)
SAVEFILE	(Savfil) (Dayinc) (Savfl2)	
where:	Savfil Dayinc Savfl2	Specifies name of disk file to be used for storing intermediate results (default = TMP.FIL) file is overwritten after each dump) Number of days between dumps (optional: default is 1) Optional second disk filename to be used on alternate dumps - eliminates risk of system crash during the dump. If blank, file is overwritten each time.
INITFILE	(Inifil)	
where:	Inifil	Specifies name of disk file of intermediate results to be used for initializing run (default = TMP.FIL)
MULTYEAR	H6H Savfil (Inifil)	
where:	H6H Savfil Inifil	Specifies the High-Sixth-High is being calculated for use in pre-1997 PM10 processing Specifies name of disk file to be used for storing results at end of the year Optional name of disk file used for initializing the results arrays from previous year(s). The Inifil parameter is not used for the first year in the multi-year run.
DEBUGOPT	MODEL (Dbgfil) and/or METEOR (Dbmfil)	
where:	MODEL (Dbgfil) METEOR (Dbmfil)	Specifies that MODEL debugging output will be generated Optional filename for the model calculation debug file Specifies that METEORological profile data file will be generated Optional filename for the meteorological profile data file
ERRORFIL	(Errfil)	
where:	Errfil	Specifies name of detailed error listing file (default = ERRORS.LST)

TABLE B-3

DESCRIPTION OF SOURCE PATHWAY KEYWORDS

SO Keywords	Type	Keyword Description
STARTING	M - N	Identifies the start of SOURCE pathway inputs
ELEVUNIT	O - N	Defines input units for source elevations (defaults to meters), must be first keyword after SO STARTING if used.
LOCATION	M - R	Identifies coordinates for particular source
SRCPARAM	M - R	Identifies source parameters for a particular source
BUILDHGT	O - R	Building height values for each wind sector
BUILDWID	O - R	Building width values for each wind sector
XBADJ	O - R	Along-flow distances from the stack to the center of the upwind face of the projected building
YBADJ	O - R	Across-flow distances from the stack to the center of the upwind face of the projected building
AREAVERT	M - R	Specifies location of vertices for an AREAPOLY source type (mandatory if AREAPOLY source is used)
URBANSRC	O - R	Identifies which sources to model with urban effects
EMISFACT	O - R	Optional input for variable emission rate factors
EMISUNIT	O - N	Optional unit conversion factors for emissions, concentrations
HOUREMIS	O - R	Option for specifying hourly emission rates in a separate file
INCLUDED	O - R	Option to include data from a separate file in the runstream
SRCGROUP[1]	M - R	Identification of source groups
FINISHED	M - N	Identifies the end of SOURCE pathway inputs

1) Source groups are treated independently for AERMOD.

TABLE B-4

DESCRIPTION OF SOURCE PATHWAY KEYWORDS AND PARAMETERS

Keyword	Parameters	
ELEVUNIT	METERS or FEET	
where:	METERS	Specifies input units for source elevations of meters
	FEET	Specifies input units for source elevations of feet Note: This keyword applies to source elevations only.
LOCATION	Srcid Srctyp Xs Ys (Zs)	
where:	Srcid	Source identification code (alphanumeric string of up to eight characters)
	Srctyp	Source type: POINT, VOLUME, AREA, AREAPOLY, AREACIRC
	Xs	x-coord of source location, SW corner for AREA (in m)
	Ys	y-coord of source location, SW corner for AREA (in m)
	Zs	Optional z-coord of source location (elevation above mean sea level, defaults to 0.0 if omitted)
SRCPARAM	Srcid Ptemis Stkhgt Stktmp Stkvel Stkdia	(POINT source)
	Vlemis Relhgt Syinit Szinit	(VOLUME source)
	Aremis Relhgt Xinit (Yinit) (Angle) (Szinit)	(AREA source)
	Aremis Relhgt Nverts (Szinit)	(AREAPOLY source)
	Aremis Relhgt Radius (Nverts) (Szinit)	(AREACIRC source)
where:	Srcid	Source identification code
	__Emis	Source emission rate: in g/s for Ptemis or Vlemis, g/(s-m^2) for Aremis for concentration
	___Hgt	Source physical release height above ground (center of height for VOLUME)
	Stktmp	Stack gas exit temperature (K)
	Stkvel	Stack gas exit velocity (m/s)
	Stkdia	Stack inside diameter (m)
	Syinit	Initial lateral dimension of VOLUME source (m)
	Szinit	Initial vertical dimension of VOLUME or AREA source (m)
	Xinit	Length of side of AREA source in X-direction (m)
	Yinit	Length of side of AREA source in Y-direction (m) (optional parameter, assumed to be equal to Xinit if omitted)
	Angle	Orientation angle of AREA source relative to North (degrees), measured positive clockwise, rotated around the source location, (Xs,Ys) (optional parameter, assumed to be 0.0 if omitted)
	Nverts	Number of vertices used for AREAPOLY or AREACIRC source (between 3 and 20, optional for AREACIRC sources)
	Radius	Radius of circular area for AREACIRC source (m)
BUILDHGT	Srcid (or Srcrng) Dsbh(i), i=1,36	
where:	Srcid	Source identification code
	Srcrng	Range of sources (inclusive) for which building dimensions apply, entered as two alphanumeric strings separated by a '-'
	Dsbh	Array of direction-specific building heights (m) beginning with 10 degree flow vector and increment-ing by 10 degrees clockwise
BUILDWID	Srcid (or Srcrng) Dsbw(i), i=1,36	
where:	Srcid	Source identification code
	Srcrng	Range of sources (inclusive) for which building dimensions apply
	Dsbw	Array of direction-specific building widths (m) beginning with 10 degree flow vector and increment-ing by 10 degrees clockwise

TABLE B-4 (CONT.)
DESCRIPTION OF SOURCE PATHWAY KEYWORDS AND PARAMETERS

XBADJ	Srcid (or Srcrng) Xbadj(i), i=1,36	
where:	Srcid Srcrng Xbadj(i)	Source identification code Range of sources (inclusive) for which XBADJ distances apply Array of direction-specific along-wind distances beginning with 10 degree flow vector and incrementing by 10 degrees clockwise
YBADJ	Srcid (or Srcrng) Ybadj(i), i=1,36	
where:	Srcid Srcrng Ybadj(i)	Source identification code Range of sources (inclusive) for which YBADJ distances apply Array of direction-specific across-wind distances beginning with 10 degree flow vector and incrementing by 10 degrees clockwise
AREAVERT	Srcid Xv(1) Yv(1) Xv(2) Yv(2) ... Xv(i) Yv(i)	
where:	Srcid Xv(1) Yv(1) Xv(i) Yv(i)	Source identification code X-coordinate of the first vertex of an AREAPOLY source (must be the same as the value of Xs for that source defined on the SO LOCATION card) Y-coordinate of the first vertex of an AREAPOLY source (must be the same as the value of Ys for that source defined on the SO LOCATION card) X-coordinate for the ith vertex of an AREAPOLY source Y-coordinate for the ith vertex of an AREAPOLY source
URBANSRC	Srcid's and/or Srcrng's	
where:	Srcid Srcrng	Specifies which source(s) will be modeled with urban effects Specifies a range of sources that will be modeled with urban effects
EMISFACT	Srcid (or Srcrng) Qflag Qfact(i), i=1,n	
where:	Srcid Srcrng Qflag Qfact	Source identification code Range of sources (inclusive) for which emission rate factors apply Variable emission rate flag: SEASON for seasona; MONTH for monthly; HROFDY for hour-of-day; WSPEED for wind speed category; SEASHR for season-by-hour; SHRDOW for season by hour-of-day by day-of-week (M-F,Sat,Sun); and SHRDOW7 for season by hour-of-day by day-of-week (M,Tu,W, Th,F,Sat,Sun) Array of scalar emission rate factors, for: SEASON, n=4; MONTH, n=12; HROFDY, n=24; WSPEED, n=6; SEASHR, n=96; SHRDOW, n=288; SHRDOW7, n=672
EMISUNIT	Emifac Emilbl Conlbl	
where:	Emifac Emilbl Conlbl	Emission rate factor used to adjust units of output (default value is 1.0 E06 for CONC for grams to micrograms) Label to use for emission units (default is grams/sec) Label to use for concentrations (default is micrograms/m^3)

TABLE B-4 (CONT.)

DESCRIPTION OF SOURCE PATHWAY KEYWORDS AND PARAMETERS

HOUREMIS	Emifil Srcid's Srcrng's	
where:	Emifil Srcid's Srcrng's	Specifies name of the hourly emission rate file Discrete source IDs that are included in the hourly emission file Source ID ranges that are included in the hourly emission file
INCLUDED	Incfil	
where:	Incfil	Specifies name of the file to be included in the runstream data
SRCGROUP	Grpid Srcid's Srcrng's	
where:	Grpid Srcid's Srcrng's	Group ID (Grpid = ALL specifies group including all sources), number of source groups limited by NGRP parameter in the computer code Discrete source IDs to be included in group Source ID ranges to be included in group Note: Card may be repeated with same Grpid if more space is needed to specify sources

TABLE B-5

DESCRIPTION OF RECEPTOR PATHWAY KEYWORDS

RE Keywords	Type	Keyword Description
STARTING	M - N	Identifies the start of RECEPTOR pathway inputs
ELEVUNIT	O - N	Defines input units for receptor elevations (defaults to meters), must be first keyword after RE STARTING if used.
GRIDCART	O - R[1]	Defines a Cartesian grid receptor network
GRIDPOLR	O - R[1]	Defines a polar receptor network
DISCCART	O - R[1]	Defines the discretely placed receptor locations referenced to a Cartesian system
DISCPOLR	O - R[1]	Defines the discretely placed receptor locations referenced to a polar system
EVALCART	O - R[1]	Defines discrete Cartesian receptor locations for use with EVALFILE output option
INCLUDED	O - R	Option to include data from a separate file in the runstream
FINISHED	M - N	Identifies the end of RECEPTOR pathway inputs

1) At least one of the following must be present: GRIDCART, GRIDPOLR, DISCCART, DISCPOLR, or EVALCART. Multiple receptor networks can be specified in a single run, including both Cartesian and polar, up to an overall maximum controlled by the NREC parameter.

TABLE B-6

DESCRIPTION OF RECEPTOR PATHWAY KEYWORDS AND PARAMETERS

Keyword	Parameters	
ELEVUNIT	METERS or FEET	
where:	METERS	Specifies input units for receptor elevations of meters
	FEET	Specifies input units for receptor elevations of feet Note: This keyword applies to receptor elevations only.
GRIDCART	Netid STA XYINC Xinit Xnum Xdelta Yinit Ynum Ydelta or XPNTS Gridx1 Gridx2 Gridx3 .... GridxN, and YPNTS Gridy1 Gridy2 Gridy3 .... GridyN ELEV Row Zelev1 Zelev2 Zelev3 ... ZelevN HILL Row Zhill1 Zhill2 Zhill3 ... ZhillN FLAG Row Zflag1 Zflag2 Zflag3 ... ZflagN END	
where:	Netid	Receptor network identification code (up to eight alphanumeric characters)
	STA	Indicates STArt of GRIDCART subpathway, repeat for each new Netid
	XYINC	Keyword identifying grid network generated from x and y increments
	Xinit	Starting x-axis grid location in meters
	Xnum	Number of x-axis receptors
	Xdelta	Spacing in meters between x-axis receptors
	Yinit	Starting y-axis grid location in meters
	Ynum	Number of y-axis receptors
	Ydelta	Spacing in meters between y-axis receptors
	XPNTS	Keyword identifying grid network defined by a series of x and y coordinates
	Gridx1	Value of first x-coordinate for Cartesian grid
	GridxN	Value of 'nth' x-coordinate for Cartesian grid
	YPNTS	Keyword identifying grid network defined by a series of x and y coordinates
	Gridy1	Value of first y-coordinate for Cartesian grid
	GridyN	Value of 'nth' y-coordinate for Cartesian grid
	ELEV	Keyword to specify that receptor elevations follow
	Row	Indicates which row (y-coordinate fixed) is being input
	Zelev	An array of receptor terrain elevations for a particular Row
	HILL	Keyword to specify that hill height scales follow
	Row	Indicates which row (y-coordinate fixed) is being input
	Zhill	An array of receptor hill height scales for a particular Row
	FLAG	Keyword to specify that flagpole receptor heights follow
	Row	Indicates which row (y-coordinate fixed) is being input
	Zflag	An array of receptor heights above local terrain elevation for a particular Row (flagpole receptors)
	END	Indicates END of GRIDCART subpathway, repeat for each new Netid

TABLE B-6 (CONT.)

DESCRIPTION OF RECEPTOR PATHWAY KEYWORDS AND PARAMETERS

GRIDPOLR	Netid STA ORIG Xinit Yinit, or ORIG Srcid DIST Ring1 Ring2 Ring3 ... RingN DDIR Dir1 Dir2 Dir3 ... DirN, or GDIR Dirnum Dirini Dirinc ELEV Dir Zelev1 Zelev2 Zelev3 ... ZelevN HILL Dir Zhill1 Zhill2 Zhill3 ... ZhillN FLAG Dir Zflag1 Zflag2 Zflag3 ... ZflagN END	
where:	Netid	Receptor network identification code (up to eight alphanumeric characters)
	STA	Indicates STArt of GRIDPOLR subpathway, repeat for each new Netid
	ORIG	Optional keyword to specify the origin of the polar network (assumed to be at x=0, y=0 if omitted)
	Xinit	x-coordinate for origin of polar network
	Yinit	y-coordinate for origin of polar network
	Srcid	Source ID of source used as origin of polar network
	DIST	Keyword to specify distances for the polar network
	Ring1	Distance to the first ring of polar coordinates
	RingN	Distance to the 'nth' ring of polar coordinates
	DDIR	Keyword to specify discrete direction radials for the polar network
	Dir1	First direction radial in degrees (1 to 360)
	DirN	The 'nth' direction radial in degrees (1 to 360)
	GDIR	Keyword to specify generated direction radials for the polar network
	Dirnum	Number of directions used to define the polar system
	Dirini	Starting direction of the polar system
	Dirinc	Increment (in degrees) for defining directions
	ELEV	Keyword to specify that receptor elevations follow
	Dir	Indicates which direction is being input
	Zelev	An array of receptor terrain elevations for a particular direction radial
	HILL	Keyword to specify that hill height scales follow
	Dir	Indicates which direction is being input
	Zhill	An array of receptor hill height scales for a particular direction radial
	FLAG	Keyword to specify that flagpole receptor heights follow
	Dir	Indicates which direction is being input
	Zflag	An array of receptor heights above local terrain elevation for a particular direction (flagpole receptors)
	END	Indicates END of GRIDPOLR subpathway, repeat for each new Netid

TABLE B-6 (CONT.)

DESCRIPTION OF RECEPTOR PATHWAY KEYWORDS AND PARAMETERS

DISCCART	Xcoord Ycoord (Zelev Zhill) (Zflag)	
where:	Xcoord	x-coordinate for discrete receptor location
	Ycoord	y-coordinate for discrete receptor location
	Zelev	Elevation above sea level for discrete receptor location (optional), used only for ELEV terrain
	Zhill	Hill height scale corresponding with a discrete receptor location (optional), used only for ELEV terrain
	Zflag	Receptor height (flagpole) above local terrain (optional), used only with FLAGPOLE keyword
DISCPOLR	Srcid Dist Direct (Zelev Zhill) (Zflag)	
where:	Srcid	Specifies source identification for which discrete polar receptor locations apply (used to define the origin for the discrete polar receptor)
	Dist	Downwind distance to receptor location
	Direct	Direction to receptor location, in degrees clockwise from North
	Zelev	Elevation above sea level for receptor location (optional), used only for ELEV terrain
	Zhill	Hill height scale corresponding with a discrete receptor location (optional), used only for ELEV terrain
	Zflag	Receptor height (flagpole) above local terrain (optional), used only with FLAGPOLE keyword
EVALCART	Xcoord Ycoord Zelev Zhill Zflag Arcid (Name)	
where:	Xcoord	x-coordinate for discrete receptor location
	Ycoord	y-coordinate for discrete receptor location
	Zelev	Elevation above sea level for discrete receptor location (optional), used only for ELEV terrain
	Zhill	Hill height scale corresponding with a discrete receptor location (optional), used only for ELEV terrain
	Zflag	Receptor height (flagpole) above local terrain (optional), used only with FLAGPOLE keyword
	Arcid	Receptor arc ID used to group receptors along an arc or other grouping (up to eight characters)
	(Name)	Optional name for receptor (up to eight characters)
INCLUDED	Incfil	
where:	Incfil	Specifies name of the file to be included in the runstream data

TABLE B-7

DESCRIPTION OF METEOROLOGY PATHWAY KEYWORDS

ME Keywords	Type	Keyword Description
STARTING	M - N	Identifies the start of METEOROLOGY pathway inputs
SURFFILE	M - N	Describes input meteorological surface data file
PROFFILE	M - N	Describes input meteorological profile data file
SURFDATA	M - N	Describes surface meteorological station
UAIRDATA	M - N	Describes upper air meteorological station
SITEDATA	O - N	Describes on-site meteorological station
PROFBASE	M - N	Specifies the base elevation for the potential temperature profile
STARTEND	O - N	Specifies start and end dates to be read from input meteorological data file (default is to read entire file)
DAYRANGE	O - R	Specifies days or ranges of days to process (default is to process all data read in)
SCIMBYHR	O - N	Specifies the parameters for the SCIM (Sampled Chronological Input Model) option (see CO MODELOPT)
WDROTATE	O - N	May be used to correct for alignment problems of wind direction measurements, or to convert wind direction <u>from</u> to flow vector
WINDCATS	O - N	Input upper bounds of wind speed categories, five values input - sixth category is assumed to have no upper bound
FINISHED	M - N	Identifies the end of METEOROLOGY pathway inputs

TABLE B-8

DESCRIPTION OF METEOROLOGY PATHWAY KEYWORDS AND PARAMETERS

Keyword	Parameters	
SURFFILE	Sfcfil (Format)	
where:	Sfcfil Format	Specify filename for surface meteorological input file Specify format for input file
PROFFILE	Profil (Format)	
where:	Profil Format	Specify filename for profile meteorological input file Specify format for input file
SURFDATA	Stanum Year (Name) (Xcoord Ycoord)	
where:	Stanum Year Name Xcoord Ycoord	Station number, e.g. 5-digit WBAN number for NWS surface station Year of data being processed (four digits) Station name (optional) x-coordinate of station location (m) (optional) y-coordinate of station location (m) (optional)
UAIRDATA	Stanum Year (Name) (Xcoord Ycoord)	
where:	Stanum Year Name Xcoord Ycoord	Station number, e.g. 5-digit WBAN number for NWS upper air station Year of data being processed (four digits) Station name (optional) x-coordinate of station location (m) (optional) y-coordinate of station location (m) (optional)
SITEDATA	Stanum Year (Name) (Xcoord Ycoord)	
where:	Stanum Year Name Xcoord Ycoord	Station number for on-site meteorological data station Year of data being processed (four digits) Station name (optional) x-coordinate of station location (m) (optional) y-coordinate of station location (m) (optional)
PROFBASE	BaseElev (Units)	
where:	BaseElev Units	Base elevation (above MSL) for the potential temperature profile Units of BaseElev: METERS or FEET (default is METERS)
STARTEND	Strtyr Strtmn Strtdy (Strthr) Endyr Endmn Enddy (Endhr)	
where:	Strtyr Strtmn Strtdy Strthr Endyr Endmn Enddy Endhr	Year of first record to be read Month of first record to be read Day of first record to be read Hour of first record to be read (optional) Year of last record to be read Month of last record to be read Day of last record to be read Hour of last record to be read (optional) Note: File read begins with hour 1 of the start date and ends with hour 24 of the end date if Stahr and Endhr are omitted.

TABLE B-8 (CONT.)

DESCRIPTION OF METEOROLOGY PATHWAY KEYWORDS AND PARAMETERS

DAYRANGE	Range1 Range2 Range3 ... RangeN	
where:	Range1	First range of days to process, either as individual day (XXX) or as range (XXX-YYY); days may be input as Julian dates (XXX) or as month and day (XX/YY)
	RangeN	The 'nth' range of days to process
SCIMBYHR	NRegStart NRegInt NWetStart NWetInt (SfcFilnam PflFilnam)	
where:	NRegStart	Specifies the first hour to be sampled with the SCIM option; required to have a value from 1 to 24
	NregInt	Specifies the sampling interval, in hours
	NWetStart	Specifies the first wet hour to be sampled with the SCIM option (not currently used in AERMOD, should set to 0)
	NWetInt	Specifies the wet sampling interval, in hours (not currently used in AERMOD, should be set to 0)
	SfcFilnam	Optional output file name to list the surface meteorological data for the sampled hours
	PflFilnam	Optional output file name to list the profile meteorological data for the sampled hours
WDROTATE	Rotang	
where:	Rotang	Specifies angle (in degrees) to rotate wind direction measurements to correct for alignment problems; value of Rotang is subtracted from WD measurements, i.e., rotation is counterclockwise
WINDCATS	Ws1 Ws2 Ws3 Ws4 Ws5	
where:	Ws1	Upper bound of first wind speed category (m/s)
	Ws2	Upper bound of second wind speed category (m/s)
	Ws3	Upper bound of third wind speed category (m/s)
	Ws4	Upper bound of fourth wind speed category (m/s)
	Ws5	Upper bound of fifth wind speed category (m/s) (sixth category is assumed to have no upper bound)

TABLE B-9

DESCRIPTION OF EVENT PATHWAY KEYWORDS

EV Keywords	Type	Keyword Description
STARTING	M - N	Identifies the start of EVENT pathway inputs
EVENTPER	M - R	Describes data and averaging period for an event
EVENTLOC	M - R	Describes receptor location for an event
FINISHED	M - N	Identifies the end of EVENT pathway inputs

TABLE B-10

DESCRIPTION OF EVENT PATHWAY KEYWORDS AND PARAMETERS

Keyword	Parameters	
EVENTPER	Evname Aveper Grpid Date	
where:	Name	Specify name of event to be processed (e.g. H2H24ALL), (up to eight alphanumeric characters)
	Grpid	Specify source group ID for event
	Aveper	Specify averaging period for event
	Date	Specify data period for event (ending YYMMDDHH for averaging period)
EVENTLOC	Evname XR= Xr YR= Yr (Zelev) (Zflag) or RNG= Rng DIR= Dir (Zelev) (Zflag)	
where:	Evname	Specify name of event to be processed (e.g. H2H24ALL), (up to eight alphanumeric characters)
	XR=	X-coordinate for event (discrete Cartesian receptor)
	YR=	Y-coordinate for event (discrete Cartesian receptor)
	RNG=	Distance range for event (discrete polar receptor)
	DIR=	Radial direction for event (discrete polar receptor)
	Zelev	Terrain elevation for event (optional)
	Zflag	Receptor height above ground for event (optional)

Note: EVENT locations can be input as either discrete Cartesian receptors (XR=, YR=) or as discrete polar receptors (RNG=, DIR=). Events that are specified in the file generated by the AERMOD model (CO EVENTFIL card) are always given as discrete Cartesian coordinates. Discrete polar receptors are assumed to be relative to an origin of (0,0).

TABLE B-11

DESCRIPTION OF OUTPUT PATHWAY KEYWORDS

OU Keywords	Type	Keyword Description
STARTING	M - N	Identifies the start of OUTPUT pathway inputs
RECTABLE	O - R	Option to specify value(s) by receptor for output
MAXTABLE	O - R	Option to summarize the overall maximum values
DAYTABLE	O - N	Option to print summaries for each averaging period for each day processed.
MAXIFILE	O - R	Option to list events exceeding a threshold value to file (if CO EVENTFIL option is used, these events are included in the input file generated for the EVENT model).
POSTFILE[1]	O - R	Option to write results to a mass storage file for postprocessing.
PLOTFILE[1]	O - R	Option to write certain results to a storage file suitable for input to plotting routines
TOXXFILE	O - R	Option to write results to a storage file suitable for input to the TOXX model component of TOXST or the RISK
RANKFILE	O - R	Option to output file of ranked values for Q-Q plots (must be used with the MAXTABLE keyword)
EVALFILE	O - R	Option to output file of normalized arc maxima from EVALCART receptors for model evaluation studies
EVENTOUT	M - N	Specifies the level of output information provided for EVENT processing
FINISHED	M - N	Identifies the end of OUTPUT pathway inputs

1) POSTFILE is used to output concurrent concentration values for particular source groups and averaging times across the receptor network, suitable for postprocessing, such as might be done for implementing the intermediate terrain policy. PLOTFILE is used to output specific design values, such as second high concentrations, across the receptor network, suitable for plotting concentration contours.

TABLE B-12

DESCRIPTION OF OUTPUT PATHWAY KEYWORDS AND PARAMETERS

Keyword	Parameters	
RECTABLE	Aveper FIRST SECOND . . . SIXTH or Aveper 1ST 2ND . . . 6TH	
where:	Aveper FIRST SECOND SIXTH 1ST 2ND 6TH	Averaging period to summarize with high values (keyword ALLAVE specifies all averaging periods) Select summaries of FIRST highest values by receptor Select summaries of SECOND highest values by receptor Select summaries of SIXTH highest values by receptor Select summaries of 1ST highest values by receptor Select summaries of 2ND highest values by receptor Select summaries of 6TH highest values by receptor Note: If two keywords are input separated by a dash (e.g. FIRST-THIRD), then summaries of all high values in that range are provided. The number of high values allowed is controlled by the NVAL parameter in the computer code (initially set at 3). Also, if the CO EVENTFIL keyword is exercised, then the events generated by the RECTABLE keyword are included in the input file for EVENT model.
MAXTABLE	Aveper Maxnum	
where:	Aveper Maxnum	Averaging period to summarize with maximum values (keyword ALLAVE specifies all averaging periods) Specifies number of overall maximum values to summarize (number of maximum values permitted is limited by the NMAX parameter in the computer code, initially set at 50)
DAYTABLE	Avper1 Avper2 Avper3 . . .	
where:	Avper1	Averaging period to summarize with values by receptor for each day of data processed (keyword ALLAVE for first parameter specifies all averaging periods) Averaging period to summarize with maximum values (keyword ALLAVE specifies all averaging periods) Specifies number of overall maximum values to summarize (number of maximum values permitted is limited by the NMAX parameter in the computer code, initially set at 50)

TABLE B-12 (CONT.)

DESCRIPTION OF OUTPUT PATHWAY KEYWORDS AND PARAMETERS

MAXIFILE	Aveper Grpid Thresh Filnam (Funit)	
where:	Aveper	Specifies averaging period for list of values equal to or exceeding a threshold value
	Grpid	Specifies source group to be output to file
	Thresh	Threshold value (e.g. NAAQS) for list of exceedances
	Filnam	Name of disk file to store maximum values
	Funit	Optional parameter to specify the file unit Note: If the CO EVENTFIL keyword is exercised, then the events generated by the MAXIFILE keyword are included in the input file for EVENT processing.
POSTFILE	Aveper Grpid Format Filnam (Funit)	
where:	Aveper	Specifies averaging period to be output to file, e.g., 24 for 24-hr averages, PERIOD for period averages
	Grpid	Specifies source group to be output to file
	Format	Specifies format of file, either UNFORM for unformatted files or PLOT for formatted files for plotting
	Filnam	Specifies filename for output file
	Funit	Optional parameter to specify the file unit
PLOTFILE	Aveper Grpid Hivalu Filnam (Funit) (Short Term values) Aveper Grpid Filnam (Funit) (PERIOD or ANNUAL averages)	
where:	Aveper	Specifies averaging period to be output to file, e.g., 24 for 24-hr averages, PERIOD for period averages, WINTER for winter averages, etc.
	Grpid	Specifies source group to be output to file
	Hivalu	Specifies high value summary (e.g. FIRST, SECOND, 1ST, 2ND, etc.) to be output to file (must be selected on a RECTABLE card)
	Filnam	Specifies filename for output file
	Funit	Optional parameter to specify the file unit
TOXXFILE	Aveper Cutoff Filnam (Funit)	
where:	Aveper	Specifies averaging period to be output to file, e.g., 1 for 1-hr averages.
	Cutoff	Specifies cutoff (threshold) value in g/m^3 for outputting results for AERMOD model
	Filnam	Specifies filename for output file
	Funit	Optional parameter to specify the file unit
RANKFILE	Aveper Hinum Filnam (Funit)	
where:	Aveper	Specifies averaging period to be output to file, e.g., 24 for 24-hr averages
	Hinum	Specifies the number of high values to be ranked
	Filnam	Specifies filename for output file
	Funit	Optional parameter to specify the file unit
EVALFILE	Srcid Filnam (Funit)	
where:	Srcid	Specifies the source ID to be output to file
	Filnam	Specifies filename for output file
	Funit	Optional parameter to specify the file unit
EVENTOUT	SOCONT or DETAIL	
where:	SOCONT	Provide source contribution information only in the event output
	DETAIL	Include hourly concentrations for each source and hourly meteorological data in the event output

APPENDIX C. EXPLANATION OF ERROR MESSAGE CODES

C.1 INTRODUCTION

The AERMOD input runstream is checked to identify parameters that are missing or potentially in error, and the input source and meteorological data are checked and flagged for possible erroneous values.

The AERMOD model uses a "defensive programming" approach to eliminate as much as possible of the user's work in debugging the input runstream file. Also, a great deal of effort has been made to eliminate the possibility of run time errors, such as "divide by zero," and to point out questionable input data. Error messages are reported to the user in two ways. A summary of messages is provided in the main output result file, and the user can also request a detailed message listing file.

Message Summary: Whether the user selects a detailed error listing file or not, the AERMOD model output a summary of messages within the output result file. This message table gives the number of messages of each type, together with a detailed list of all the fatal errors and warning messages. During setup processing, if no errors or warnings are generated, then the model simply reports to the user that "SETUP Finishes Successfully."

Detailed Message Listing File: The AERMOD model provide the option of saving a detailed list of all messages generated by the model in a separate output file. The user can select this option by specifying the keyword "ERRORFIL" followed by a filename inside the COntrol pathway. For example, the following statements will save all the error messages to an ASCII text file named "errormsg.out":

```
CO  STARTING
    ERRORFIL  errormsg.out
CO  FINISHED
```

C.2 THE OUTPUT MESSAGE SUMMARY

There are two message summaries provided in the standard output file of the AERMOD model. The first one is located after the echo of input runstream file images and before the input data summary. This summary will take one of two forms, depending on whether any fatal error or non-fatal warning messages were generated, and also depending on whether the option to RUN or NOT to run was selected on the CO RUNORNOT card. If there are no errors or warnings generated during the setup processing, and the RUN option was selected, then the model simply reports that "SETUP Finishes Successfully." If any fatal errors or warning messages were generated during the setup processing, or if the option NOT to run was selected, then a more detailed summary is provided. This summary provides a message count for each type of message, and a detailed listing of each fatal error and warning message generated. The second message summary table is located at the very end of the standard output result file, and it sums up the messages generated by the complete model run - both setup processing and run-time processing.

An example of a setup processing message summary is shown in Figure C-1.

```
*** Message Summary For The AERMOD Model Setup ***

 --------- Summary of Total Messages ---------

A Total of           0 Fatal Error Message(s)
A Total of           0 Warning Message(s)
A Total of           0 Information Message(s)


   ******** FATAL ERROR MESSAGES ********
                ***  NONE  ***

   ********   WARNING MESSAGES   ********
                ***  NONE  ***

   ***********************************
   *** SETUP Finishes Successfully ***
   ***********************************
```

FIGURE C-1. EXAMPLE OF AN AERMOD MESSAGE SUMMARY

C.3 DESCRIPTION OF THE MESSAGE LAYOUT

Three types of messages can be produced by the model during the processing of input runstream images and during model calculations. These are described briefly below:

- Errors that will halt any further processing, except to identify additional error conditions (type E);
- Warnings that do not halt processing but indicate possible errors or suspect conditions (type W); and
- Informational messages that may be of interest to the user but have no direct bearing on the validity of the results (type I).

The messages have a consistent structure which contains the pathway ID, indicating which pathway the messages are generated from; the message type followed by a three-digit message number; the line number of the input runstream image file for setup messages (or the meteorology hour number for runtime messages); the name of the module (e.g. the subroutine name) from which the message is generated; a detailed message corresponding to the message code; and an 8-character simple hint to help the user spot the possible source of the problem.

The following is an example of a detailed message generated from the CO pathway:

```
CO E100    8 EXPATH: Invalid Pathway Specified. The Troubled Pathway is FF
```

The message syntax is explained in more detail below (values in parentheses give the column numbers within the message line for each element):

```
PW Txxx LLLL mmmmmm: MESSAGE Hints
```

- Hints to help you determine the nature of errors (keyword, pathway where the error occurs, ... etc.) (73:80)
- Detailed message for this code (22:71)
- Name of the code module from which the message is generated (14:19)
- The line number of the input runstream image file where the message occurs; If message occurs in runtime operation, the hour number of the meteorology file is given (9:12)
- Numeric message code (a 3-digit number) (5:7)
- Message type (E, W, I) (4:4)
- Pathway ID (CO, SO, RE, ME, EV, or OU) (1:2) or MX for meteorological data extraction, or CN for calculation messages

If an error occurs during processing of an included file (either SO INCLUDED or RE INCLUDED), the line number will represent the line number of the included file. The line number of the runstream file is saved before processing the included data, and then restored when processing returns to the main runstream file.

The three message types are identified with the letters E (for errors), W (for warnings), and I (for informational messages). The 3-digit message codes are grouped into general categories corresponding to the different stages of the processing. Theses categories are:

100 - 199 Input Runstream Image Structure Processing
200 - 299 Parameter Setup Processing
300 - 399 Data and Quality Assurance Processing
400 - 499 Run Time Message Processing
500 - 599 Input/Output Message Processing

A detailed description of each of the message codes currently used in the model is provided in the next section.

C.4 DETAILED DESCRIPTION OF THE ERROR/MESSAGE CODES

INPUT RUNSTREAM IMAGE STRUCTURE PROCESSING, 100-199

This type of message indicates problems with the basic syntax and/or structure of the input runstream image. Typical messages include errors like "Missing mandatory keyword", "Illegal Keyword", ..., etc. If a fatal error of this kind is detected in a runstream image, a fatal error message is written to the message file and any attempt to process data is prohibited, although the remainder of the runstream file is examined for other possible errors. If a warning occurs, data may still be processed, although the inputs should be checked carefully to be sure that the condition causing the warning does not indicate an error.

100 Invalid Pathway Specified. The pathway ID should be a 2 character string. It should be one of the following: CO for control pathway, SO for source pathway, RE for receptor pathway (or EV for event pathway for EVENT processing), ME for meteorology data setting pathway, and OU for output format pathway. Its position is normally confined to columns 1 and 2 (1:2) of the input runstream file. However, the model does allow for a shift of the entire input runstream file of up to 3 columns. If the inputs are shifted, then all input records <u>must</u> be shifted by the same amount. The invalid pathway is repeated at the end of the message.

105 Invalid Keyword Specified. The keyword ID should be an 8-character string. Its position is normally confined to columns 4 to 11 (4:11) of the input runstream file. However, the model does allow for a shift of the entire input runstream file of up to 3 columns. If the inputs are shifted, then all input records must be shifted by the same amount. There should be a space between keyword ID and any other data fields. For a list of valid keywords, refer to Appendix A or Appendix B. The invalid keyword is repeated at the end of the message.

110 Keyword is Not Valid for This Pathway. The input keyword is a valid 8-character string, but it is not valid for the particular pathway. Refer to Appendix A, Appendix B or Section 3 for the correct usage of the keyword. The invalid keyword is repeated at the end of the message.

115 Starting and Finishing Statements do not match. Only One STARTING and one FINISHED statement,respectively, is allowed at the very beginning and the very end of each pathway block. Check the position and frequency to make sure the input runstream file meets the format requirement. The pathway during which the error occurs is included at the end of the message.

120 Pathway is Out of Sequence. The pathways are not input in the correct order. The correct order is CO, SO, RE, ME, and OU for the AERMOD and AERMOD model, and CO, SO, ME, EV, and OU for EVENT processing. The offending pathway is given as a hint.

125 Missing FINISHED Statement - Runstream file is incomplete. One or more FINISHED statements are missing. A 5-digit status variable is given as a hint. Each digit corresponds to a pathway in the appropriate order, and is a '1' if the pathway is complete and a '0' if the FINISHED is missing. For example, a status of '10111' indicates that the SO pathway was missing a FINISHED statement. Normally such an error will generate additional messages as well.

130 Missing Mandatory Keyword. To run the model, certain mandatory keywords must present in the input runstream file. For a list of mandatory keywords, see Appendix A or Appendix B. For more detailed information on keyword setup, see the description of message code 105. The missing keyword is included with the message.

135 Duplicate Non-repeatable Keyword Encountered. More than one instance of a non-repeatable keyword is encountered. For a list of non-repeatable keywords, see Appendix A or Appendix B. The repeated keyword is included with the message.

140 Invalid Placement of Keyword. A keyword has been placed out of the acceptable order, or a STARTING or FINISHED keyword has been placed in an INCLUDED file. The order for most keywords is not critical, but the relative order of a few keywords is important for the proper interpretation of the input data. The keyword reference in Section 3 identifies any requirements for the order of keywords. The keyword that was improperly placed is included with the message.

145 Conflicting Options: MULTYEAR and Re-Start Option. The multiple year option for processing PM-10 values makes use of the re-start routines in the model with some slight changes to handle the period averages from year to year. As a result, the MULTYEAR keyword cannot be specified with either the SAVEFILE or INITFILE keywords.

150 Conflicting Options: MULTYEAR for Wrong Pollutant. The multiple year option is provided specifically for the processing of PM-10 values to obtain the "high-sixth-high in five years" design value. Its treatment of the high short term values for multiple year periods is not consistent with existing air quality standards for other pollutants. To use the MULTYEAR option, the user must specify a pollutant type (on the CO POLLUTID card) of PM-10, PM10, or OTHER.

152 ELEVUNIT card must be first for this pathway. The ELEVUNIT card must be the first non-commented card after STARTING when used on the SO or RE pathway. This requirement is made in order to simplify reviewing runstream files to determine the elevation units used for sources and receptors.

154 Conflicting Options: SCIM option cannot be used with the specified option, causing a fatal error.

155 Conflicting Decay Keyword. The AERMOD model allows for the user to specify the rate of exponential decay either in terms of the half-life (HALFLIFE keyword) or the decay coefficient (DCAYCOEF keyword). If both keywords are specified, then only the first one will be used, and inputs for the second one will be ignored.

156 Option ignored - not valid with SCIM. The specified option is not valid with the SCIM option and is ignored. This is not a fatal error.

157 Wet SCIM option is not operational yet and the input is ignored. Since the model does not include wet deposition algorithms yet, the wet SCIM option is not operational.

158 Wet SCIM option is not operational yet and the input is ignored. Since the model does not include wet deposition algorithms yet, the wet SCIM option is not operational.

160 Duplicate ORIG Secondary Keyword for GRIDPOLR. Only one origin card may be specified for each grid of polar receptors. The network ID for the effected grid is included with the message.

170 Invalid Secondary Key for Receptor GRID. The network ID for the effected grid is included with this message. Refer to Appendix B for the correct syntax of secondary keywords.

175 Missing Secondary Keyword END for Receptor Grid. The END secondary keyword is required for each grid of receptors input by the user (keywords GRIDCART and

GRIDPOLR). It signals the end of inputs and triggers the processing of data for that particular network.

180 Conflicting Secondary Keyword for Receptor Grid. Two incompatible secondary keywords have been input for the same grid of receptors, e.g. GDIR and DDIR for the keyword GRIDPOLR, where GDIR specifies to generate directions with uniform spacing, and DDIR specifies that discrete, non-uniform directions are being specified.

185 Missing Receptor Keywords. No Receptors Specified. Since none of the RE pathway keywords are mandatory, a separate error check is made to determine if any of the RE keywords are specified. At least one of the following keywords must be present: GRIDCART, GRIDPOLR, DISCCART, DISCPOLR, or EVALCART.

190 No Keywords for OU Pathway and No PERIOD or ANNUAL Averages. All of the OU pathway keywords are optional, and in fact the model will run if no keywords are specified on the OU pathway as long as PERIOD or ANNUAL averages are being calculated. However, if there are no OU keywords and no PERIOD or ANNUAL averages, then there will be no output generated by the model, and this fatal error message will be generated.

195 Incompatible Option Used With SAVEFILE or INITFILE. Either a non-fatal message to warn the user that DAYTABLE results will be overwritten if the model run is re-started, or a fatal error message generated if the TOXXFILE option is selected with either the SAVEFILE or INITFILE options.

197 Post-1997 PM_{10} processing option without the MAXIFILE option is incompatible with the EVENTFIL option. Threshold violations generated through the MAXIFILE option are the only events that are compatible with post-1997 PM_{10} processing for EVENT processing.

198 The non-default TOXICS option is required in order to use the specified option, such as the SCIM option.

PARAMETER SETUP PROCESSING, 200-299

This type of message indicates problems with processing of the parameter fields for the runstream images. Some messages are specific to certain keywords, while others indicate general problems, such as an invalid numeric data field. If a fatal error of this kind is detected in a runstream image, a fatal error message is written to the message file and any attempt to process data is prohibited, although the remainder of the runstream file is examined for other

possible errors. If a warning occurs, data may still be processed, although the inputs should be checked carefully to be sure that the condition causing the warning does not indicate an error.

200 Missing Parameter(s). No options were selected for the indicated keyword. Check Appendix B for the list of parameters for the keyword in question.

201 Not Enough Parameters Specified For The Keyword. Check if there are any missing parameters following the indicated keyword. See Appendix B for the required keyword parameters.

202 Too Many Parameters Specified For The Keyword. Refer to Appendix B or Section 3 for the list of acceptable parameters.

203 Invalid Parameter Specified. The inputs for a particular parameter are not valid for some reason. Refer to Appendix B or Section 3. The invalid parameter is included with the message.

204 Option Parameters Conflict. Forced by Default to: Some parameters under the indicated keyword conflict with the other model parameters setting. Refer to Appendix B or Section 3 for the correct parameter usage. The default setting is specified with the message.

205 No Option Parameter Setting. Forced by Default to: No setting was specified for a particular parameter. Refer to Appendix B or Section 3 for the correct parameter usage. The default setting is specified with the message.

206 Regulatory DFAULT Specified With Non-default Option. The DFAULT option on the CO MODELOPT card always overrides the specified non-default option, and a warning message is generated.

207 No Parameters Specified. Default Values Used For. The keyword for which no parameters are specified is included with the message. Refer to Appendix B or Section 3 for a discussion of the default condition.

208 Illegal Numerical Field Encountered. The model may have encountered a non-numerical character for a numerical input, or the numerical value may exceed the limit on the size of the exponent, which could potentially cause an underflow or an overflow error.

209 Negative Value Appears For A Non-negative Variable. The effected variable name is provided with the message.

210 Number of Short Term Averages Exceeds Maximum. The user has specified more short term averages on the CO AVERTIME card than the model array limits allow.

This array limit is dynamically allocated at model runtime based on model inputs, and is stored in the NAVE variable. While the model still performs this test, this message should never occur.

211 Duplicate Parameter(s) Specified for Keyword. A duplicate parameter or set of parameters has been specified for the indicated keyword. For example, if more than one POSTFILE keyword is included for the same averaging period and source group, then this error message will be generated.

212 END Encountered Without (X,Y) Points Properly Set. This error occurs during setting up the grid of receptors for a Cartesian Network. This message may occur for example if X-coordinate points have been specified without any Y-coordinate points for a particular network ID.

213 ELEV Inputs Inconsistent With Option: Input Ignored. This happens when the user inputs elevated terrain heights for receptors when the FLAT option is specified. The input terrain heights are ignored and the model proceeds with FLAT terrain modeling.

214 ELEV Inputs Inconsistent With Option: Defaults Used. This happens when the user does not input elevated terrain heights for receptors when the default option of incorporating elevated terrain effects is used. The model assumes that the missing terrain heights are at 0.0 meters for those receptors and proceeds with ELEV terrain modeling.

215 FLAG Inputs Inconsistent With Option: Input Ignored. This happens when the user inputs receptor heights above ground for flagpole receptors when the FLAGPOLE keyword option has not been specified. The input flagpole heights are ignored in the model calculations.

216 FLAG Inputs Inconsistent With Option: Defaults Used. This happens when the user does not input receptor heights above ground for flagpole receptors when the FLAGPOLE keyword option has been specified. The model assumes that the missing flagpole heights are equal to the default value specified on the CO FLAGPOLE card. If no default height is specified on the FLAGPOLE card, then a default of 0.0 meters is assumed.

217 More Than One Delimiter In A Field. For example, 12//34 is an illegal input data item for the DAYRANGE card, and STACK1--STACK-20 is an illegal specification for a range of sources.

218 Number of (X,Y) Points Not Match With Number Of ELEV Or FLAG. Check the number of elevated terrain heights or flagpole receptor heights for the gridded network associated with the indicated line number in the runstream file.

219 Number Of Receptors Specified Exceeds Maximum. The user has specified more receptors on the RE pathway than the model array limits allow. This array limit is

dynamically allocated at model runtime based on model inputs, and is stored in the NREC variable. While the model still performs this test, this message should never occur.

220 Missing Origin (Use Default = 0,0) In GRIDPOLR. This is a non-fatal warning message to indicate that the ORIG secondary keyword has not been specified for a particular grid of polar receptors. The model will assume a default origin of (X=0, Y=0).

221 Missing Distance Setting In Polar Network. No distances have been provided (secondary keyword DIST) for the specified grid of polar receptors.

222 Missing Degree Or Distance Setting In Polar Network. Missing a secondary keyword for the specified grid of polar receptors.

223 Missing Distance or Degree Field. No data fields have been specified for the indicated secondary keyword.

224 Number of Receptor Networks Exceeds Maximum. The user has specified more receptor networks of gridded receptors on the RE pathway than the model array limits allow. This array limit is dynamically allocated at model runtime based on model inputs, and is stored in the NNET variable. While the model still performs this test, this message should never occur.

225 Number of X-Coords Specified Exceeds Maximum. The user has specified more X-coordinate values for a particular grid of receptors than the model array limits allow. This array limit is dynamically allocated at model runtime based on model inputs, and is stored in the IXM variable. While the model still performs this test, this message should never occur.

226 Number of Y-Coords Specified Exceeds Maximum. The user has specified more Y-coordinate values for a particular grid of receptors than the model array limits allow. This array limit is dynamically allocated at model runtime based on model inputs, and is stored in the IYM variable. While the model still performs this test, this message should never occur.

227 No Receptors Were Defined on the RE Pathway. Either through lack of inputs or through errors on the inputs, no receptors have been defined.

228 Default(s) Used for Missing Parameters on Keyword. Either an elevated terrain height or a flagpole receptor height or both are missing for a discrete receptor location. Default value(s) will be used for the missing parameter(s).

229 Too Many Parameters - Inputs Ignored on Keyword. Either an elevated terrain height or a flagpole receptor height or both are provided when the corresponding option has not been specified. The unneeded inputs are ignored.

231 Too Many Numerical Values Specified. Too many values have been specified for the type of input indicated.

232 Number Of Specified Sources Exceeds Maximum. The user has specified more sources than the model array limits allow. This array limit is dynamically allocated at model runtime based on model inputs, and is stored in the NSRC variable. While the model still performs this test, this message should never occur.

233 Building Dimensions Specified for a Non-POINT Source. Building dimensions can only be specified for a POINT source, since the VOLUME and AREA source algorithms do not include building downwash.

234 Too Many Sectors Input. For example, the user may have input too many building heights or widths for a particular source.

235 Number of Source Groups Specified Exceeds Maximum. The user has specified more source groups than the model array limits allow. This array limit is dynamically allocated at model runtime based on model inputs, and is stored in the NGRP variable. While the model still performs this test, this message should never occur.

236 Not Enough BUILDHGTs Specified for a Source ID. There should be 36 building heights.

237 Not Enough BUILDWIDs Specified for a Source ID. There should be 36 building widths.

239 Not Enough QFACTs Specified for a Source ID. The number of variable emission rate factors specified for a particular source is less than the model expects based on the variable emission rate flag. Check the EMISFACT keyword on the SO pathway in Appendix B of Section 3 for the appropriate number.

241 Not Enough BUILDLENs Specified for a Source ID. There should be 36 building lengths specified.

246 Not Enough XBADJs Specified for a Source ID. There should be 36 along-flow distances from the stack to the center of the upwind face of building specified.

247 Not Enough YBADJs Specified for a Source ID. There should be 36 across-flow distances from the stack to the center of the upwind face of building specified.

248 No Sources Were Defined on the SO Pathway. There must be at least one LOCATION card and one SRCPARAM card to define at least one source on the SO pathway. Either no cards were input or there were errors on the inputs.

250 Duplicate XPNT/DIST or YPNT/DIR Specified for GRID. One of the grid inputs, either an X-coordinate, Y-coordinate, polar distance range or polar direction, has been

specified more than once for the same grid of receptors. This generates a non-fatal warning message.

252 Duplicate Receptor Network ID Specified. A network ID for a grid of receptors (GRIDCART or GRIDPOLR keyword) has been used for more that one network.

254 Number of Receptor Arcs Exceeds Maximum. This array limit is dynamically allocated at model runtime based on model inputs, and is stored in the NARC variable. While the model still performs this test, this message should never occur.

256 EVALFILE Option Used Without EVALCART Receptors. The EVALFILE output option provides model results designed for model evaluation purposes based on receptors grouped by arc. Such receptors must be identified using the EVALCART keyword. If EVALFILE is selected without any EVALCART receptors, this fatal error message will be generated.

260 Number of Emission Factors Exceeds Maximum. The user has selected an option for variable emission rate factors that exceeds the array storage limit for emission rate factors. This array limit is dynamically allocated at model runtime based on model inputs, and is stored in the NQF variable. While the model still performs this test, this message should never occur.

262 First Vertex Does Not Match LOCATION for AREAPOLY Source. The coordinates of the first vertex defined for an AREAPOLY source must match the source location coordinates provided on the SO LOCATION card.

264 Too Many Vertices Specified for an AREAPOLY Source. The number of vertices specified on the AREAVERT cards must match the number given on the SRCPARAM card for that source.

265 Not Enough Vertices Specified for an AREAPOLY Source. The number of vertices specified on the AREAVERT cards must match the number given on the SRCPARAM card for that source.

270 Number of High Values Specified Exceeds Maximum. The user has selected a high short term value on the OU RECTABLE card that exceeds the array storage limit for high values by receptor. This array limit is dynamically allocated at model runtime based on model inputs, and is stored in the NVAL variable. While the model still performs this test, this message should never occur.

280 Number of Maximum Values Specified Exceeds Maximum. The user has selected a value for the number of overall maximum values on the OU MAXTABLE card that exceeds the array storage limit for overall maximum values. This array limit is dynamically allocated at model runtime based on model inputs, and is stored in the NMAX variable. While the model still performs this test, this message should never occur.

294 PERIOD and ANNUAL averages are both selected on the AVERTIME card. The user can only specify one long-term averaging option, either PERIOD or ANNUAL average.

295 Invalid Averaging Period Specified for the SCREEN Mode. The SCREEN mode of AERMOD can only be used with 1-hour averages.

298 Error Allocating Storage for Setup Arrays. An error occurred while allocating storage for the setup arrays, indicating that there is insufficient memory available on the computer for the model to run. Try closing other applications and/or reducing the size of the run. An estimate of memory requirements is provided on the first page of the output file.

299 Error Allocating Storage for Result Arrays. An error occurred while allocating storage for the result arrays, indicating that there is insufficient memory available on the computer for the model to run. Try closing other applications and/or reducing the size of the run. An estimate of memory requirements is provided on the first page of the output file.

SETUP DATA AND QUALITY ASSURANCE PROCESSING, 300-399

This type of message indicates problems with the actual values of the parameter data on the input runstream image. The basic structure and syntax of the input card is correct, but one or more of the inputs is invalid or suspicious. These messages include quality assurance checks on various model inputs. Typical messages will tell the consistency of parameters and data for the setup and run of the model. If a fatal error of this kind is detected in a runstream image, a fatal error message is written to the message file and any attempt to process data is prohibited. If a warning occurs, data may or may not be processed, depending on the processing requirements specified within the run stream input data.

300 Specified Source ID Has Not Been Defined Yet. The message indicates that the user attempts to use a source ID on a keyword before defining this source ID on a SO LOCATION card. It could indicate an error in specifying the source ID, an omission of a LOCATION card, or an error in the order of inputs.

310 Attempt to Define Duplicate LOCATION Card for Source. There can be only one LOCATION card for each source ID specified. The source ID is included with the message.

313 Attempt to Define Duplicate EVENTPER Card for the specified EVENT. There can be only one EVENTPER card for each EVENT specified. The EVENT name is included with the message.

315 Attempt to Define Duplicate SRCPARAM Card for Source. There can be only one SRCPARAM card for each source ID specified. The source ID is included with the message.

319 No Sources Included in the Specified Source Group. This is a non-fatal warning message indicating that a source group has been defined that does not include any sources. The source group ID is provided.

320 Source Parameter May Be Out-of-Range for Parameter. The value of one of the source parameters may be either too large or too small. The name of the parameter is provided with the message. Use the line number provided to locate the card in question.

325 Negative Exit Velocity (Set=1.0E-5) for Source ID. The exit velocity for the specified source ID was input as a negative value. Since the model currently cannot handle sources with downward momentum, the exit velocity is set to a very small value (1.0E-5 m/s) and modeling proceeds. This non-fatal message is generated to warn the user that the input may be in error.

330 Mass Fraction Parameters Do Not Sum to 1. (within +/- 2 percent) for a particular source.

332 Mass Fraction Parameter Out-of-Range for a particular source. Must be between 0.0 and 1.0, inclusive.

334 Particle Density Out-of-Range for a particular source. Must be greater than 0.0.

340 Possible error in the PROFBASE input. The value input as the base elevation (above MSL) for the potential temperature file is less than zero.

342 Source ID Mismatch in the Hourly Emissions File. The source ID read from the hourly emissions file does not match what is expected based on the SO HOUREMIS card. A source ID and/or date may be out of order or missing in the hourly emissions file. The source ID read from the file is provided with the error message.

344 Hourly Emission Rate is Zero. The emission rate read from the hourly emission file is zero for the specified date. This is written as an informational message, and does not halt processing of the data.

350 Julian Day Out Of Range. This error occurs if the Julian Day selected is less than zero or greater than 366. Check ME setup to ensure the Julian Day selection.

352 Missing Field on MULTYEAR Card for Pre-1997 PM10. When using the MULTYEAR card for pre-1997 PM10 processing, the keyword 'H6H' must be specified.

353 MULTYEAR Card for PM10 Processing Applies Only for Pre-1997 Applications. Use High-Fourth-High for Post-1997 PM10 Processing.

354 High-Fourth-High Only Required for Post-1997 PM10 Processing with the RECTABLE Card.

360 2-digit Year Specified. Valid for the range 1950-2049. Four-digit years are valid for the entire range of Gregorian dates, but two digit years are accepted.

363 24-Hr and ANNUAL Averages Only are Allowed for Post-1997 PM10 Processing on the AVERTIME Card.

365 Year Input is Greater than 2147. A four-digit year greater than 2147 has been input to the model, which will cause an integer overflow.

370 Invalid Date: 2/29 In a Non-leap Year. The year has been identified as a non-leap year, and a date of 2/29 (February 29) has been specified on the DAYRANGE card. Check the year and/or the date specification.

380 This Input Variable is Out-of-Range. The indicated value may be too large or too small. Use the line number to locate the card in question, and check the variable for a possible error.

381 Latitude in the Surface File is Not Valid. The latitude is read from the header record of the surface/scalar meteorological data file. If the value is not within the valid range of 0 to 90 degrees, then this error message is generated.

382 Error Decoding Latitude in the Surface File. The latitude is read from the header record of the surface/scalar meteorological data file. An error occurred trying to decode the latitude indicating a potential problem with the surface file.

385 Averaging period does not equal 1-hour averages for the TOXXFILE option for the AERMOD model. The AERMOD model will generate TOXXFILE outputs for other averaging periods, but the TOXX model component of TOXST currently supports only the 1-hour averages. This is a non-fatal warning message.

390 Averaging period specified on the EVENTPER card for EVENT processing must be less than or equal to 24.

391 Aspect ratio (length/width) of an area source is greater than 10. The area source algorithm in the AERMOD model allows for specifying area sources as elongated rectangles, however, if the aspect ratio exceeds 10 a warning message will be printed

out. The user should subdivide the area so that each subarea has an aspect ratio of less than 10.

392 Error Decoding Latitude. The latitude is read from the header record of the surface/scalar meteorological data file. The value of the latitude should be followed by an 'N' or an 'S' for the northern or southern hemispheres. If the value cannot be decoded properly, then this error message is generate.

395 Met. Data Error; Incompatible Version of AERMET. Based on the version date given in the header record of the surface meteorological data file, the meteorological data were generated by an older, incompatible version of AERMET.

396 Met. Data Generated by Older Version of AERMET. Based on the version date given in the header record of the surface meteorological data file, the meteorological data were generated by an older version of AERMET. The data may be compatible with the current version of AERMOD, but should be updated with the current version of AERMET.

RUNTIME MESSAGE PROCESSING, 400-499

This type of message is generated during the model run. Setup processing has been completed successfully, and the message is generated during the performance of model calculations. Typical messages will tell the information and error during the model run. If a fatal error of this kind is detected during model execution, a fatal error message is written to the message file and any further processing of the data is prohibited. The rest of the meteorological data file will be read and quality assurance checked to identify additional errors. If a warning occurs, data may or may not be processed, depending on the processing requirements specified within the run stream input data.

405 The Value of PHEE Exceeds 1.0. If the value of PHEE, the fraction of the plume material below Hcrit, is greater than 1.0, then this informational message is generated. The value of PHEE is then set to 1.0 for the specified date.

406 Increase NVMAX for complex AREAPOLY source. The number of vertices for an AREAPOLY source exceeds the value of NVMAX, initially set to 20.

410 Flow Vector Out-of-Range. The flow vector must be between 0 and 360 degrees, inclusive. The date of occurrence is provided with the message (in the form of year, month, day, hour as YYMMDDHH)

413 Number of Threshold Violation Events > 9999 for the Specified Averaging Period. This will result in duplicate event names being written to the EVENTFIL file. The duplicate events will have to be segregated before running the model in the EVENT processing mode.

420 Wind Speed Out-of-Range. The wind speed value may be either too large or too small. An error is generated if the speed is less than 0.0, and a warning is generated if the speed is greater than 30.0 m/s. The date of occurrence is provided with the message (in the form of year, month, day, hour as YYMMDDHH).

430 Ambient Temperature Data Out-of-Range. The ambient temperature value may be either too large or too small. A warning is generated if the temperature is less than 220.0 K or greater than 330 K. The date of occurrence is provided with the message (in the form of year, month, day, hour as YYMMDDHH).

432 Surface Friction Velocity Out-of-Range. The surface friction velocity may by too large. A warning is generated if the surface friction velocity is greater than 1.5 m/s. The date of occurrence is provided with the message (in the form of year, month, day, hour as YYMMDDHH).

435 Surface Roughness Length Out-of-Range. A warning is generated if the surface friction velocity is less than 0.001 meters, and the value is set to 0.001 meters to avoid a divide by zero. The date of occurrence is provided with the message (in the form of year, month, day, hour as YYMMDDHH).

438 Convective Velocity Scale Out-of-Range. The convective velocity scale may by too large. A warning is generated if the convective velocity scale is greater than 3.0 m/s. The date of occurrence is provided with the message (in the form of year, month, day, hour as YYMMDDHH).

440 Calm Hour Identified in Meteorology Data File. This message is generated if a calm hour is identified, and provides the date of occurrence (in the form of year, month, day, hour as YYMMDDHH). A calm hour is identified by a reference wind speed of 0.0 m/s in the surface meteorological data file.

450 Error in Meteorology File - Record Out of Sequence. There is an error in the sequence of the hourly meteorological data file. The message also provides the date of occurrence (in the form of year, month, day, hour as YYMMDDHH).

455 Date/Time Mismatch on Hourly Emission File. There is mismatch in the date/time field between the meteorological data file and the hourly emission file. The message also provides the date of the occurrence from the surface/scalar file (in the form of year, month, day, hour as YYMMDDHH).

456 Date/Time Mismatch on Scalar and Profile Data. There is mismatch in the date/time field between the surface/scalar and the profile meteorological data files. The message

also provides the date of the occurrence from the surface/scalar file (in the form of year, month, day, hour as YYMMDDHH).

460 Missing Hour Identified in Meteorology Data File. At least one of the meteorological variables is missing or invalid for the hour specified (in the form of year, month, day, hour as YYMMDDHH). If the missing data processing option is not used, then this message will be generated and any further calculations with the data will be aborted. The model will continue to read through the meteorological data file and check the data.

465 Number of Profile Levels Exceeds the Maximum. The profile meteorological data file includes more than the maximum number of levels, specified by the MXPLVL PARAMETER in MODULE MAIN1. The value of MXPLVL is provided with the message.

470 Mixing Height Value is Less Than or Equal to 0.0. This is an informational message that may indicate an error in the meteorological data file. The message includes the hour of occurrence (in the form of year, month, day, hour as YYMMDDHH).

475 The Reference Height is Higher than 100 m. The reference height is read from the surface/scalar meteorological data file. This warning message is generated if the reference height is higher than 100 meters. Since data for the reference height are used in surface layer similarity profiles, the reference height should be within the surface layer (between about 7 and 100 times the surface roughness length).

480 Less Than 1 Year Found for ANNUAL Averages. The input meteorological data file consists of less than a full year of data. The ANNUAL average requires that a full year of data or multiple years be available.

485 Data Remaining After End of Year. The ANNUAL average requires full years of input data (not necessarily calendar years), and there are data remaining after the end of the year. The number of hours remaining is specified.

487 User-specified Start Date on STARTEND card is Earlier Than Start Date of Data File with the ANNUAL average or post-1997 PM10 processing option.

INPUT/OUTPUT MESSAGE PROCESSING, 500-599

This type of message is generated during the model input and output. Typical messages will tell the type of I/O operation (e.g., opening, reading or writing to a file), and the type of file. If a fatal error of this kind is detected in a runstream image, a fatal error message is written to the message file and any attempt to process data is prohibited. If a warning occurs,

data may or may not be processed, depending on the processing requirements specified within the run stream input data.

500 Fatal Error Occurs During Opening of the Data File. The file specified can not be opened properly. This may be the runstream file itself, the meteorological data file, or one of the special purpose output files. This may happen when the file called is not in the specified path, or an illegal filename is specified. If no errors are found in the filename specification, then this message may also indicate that there is not enough memory available to run the program, since opening a file causes a buffer to be opened which takes up additional memory in RAM. For the special purpose output files, the hint field includes character string identifying the type of file and the file unit number, e.g., 'PLTFL312'.

510 Fatal Error Occurs During Reading of the File. File is missing, incorrect file type, or illegal data field encountered. Check the indicated file for possible problems. As with error number 500, this message may also indicate that there is not enough memory available to run the program if no other source of the problem can be identified.

520 Fatal Error Occurs During Writing to the File. Similar to message 510, except that it occurs during a write operation.

530 CAUTION! Met. Station ID Mismatch with SURFFILE for SURFDATA, UAIRDATA or SITEDATA. The surface, upper air, or optional on-site station ID numbers specified on the ME pathway do not agree with the values on the first record of the surface meteorological data file. This is a non-fatal warning message, but the input data should be checked carefully to ensure that the correct data file has been used.

540 No RECTABLE/MAXTABLE/DAYTABLE for Averaging Period. No printed output options selected for a particular averaging period. This is a non-fatal warning condition for the AERMOD model.

550 File Unit/Name Conflict for the Output Option. This error indicates that a problem exists with the filename and file unit specification for one of the special purpose output files. The associated keyword is provided as a hint. The same filename may have been used for more than one file unit, or vice versa.

560 User Specified File Unit Less Than or Equal to 25 for OU Keyword. A file unit of less than or equal to 25 has been specified for the indicated special purpose output files. This is a fatal error condition. File units of less than or equal to 25 are reserved for system files. Specify a unit number in the range of 26 to 100.

565 Possible conflict With Dynamically Allocated FUNIT. A file unit specified for the indicated special purpose output files is in the range > 100, and may therefore conflict

with file units dynamically allocated for special purpose files by the model. This is typically a non-fatal warning condition.

570 Problem Reading Temporary Event File for Event. The AERMOD model stores high value events in a temporary file that is used to create the input file for EVENT processing, if requested, and also to store the high values for the summary tables at the end of the printed output file. A problem has been encountered reading this file, possibly because the concentration value was too large and overflowed the fixed format field of F14.5.

580 End-of-File Reached Trying to Read a Data File. The AERMOD model has encountered an end-of-file trying the read the indicated file. This may appear when trying to "re-start" a model run with the CO INITFILE card if there is an error with the initialization file. Check the data file for the correct filename.

APPENDIX D. DESCRIPTION OF FILE FORMATS

D.1 AERMET METEOROLOGICAL DATA

Two files are produced for input to the AERMOD dispersion model by the AERMET meteorological preprocessor. The surface OUTPUT contains observed and calculated surface variables, one record per hour. The PROFILE file contains the observations made at each level of an on-site tower, or the one level observations taken from NWS data, one record per level per hour. The contents and format of each of these files is described below:

<u>SURFACE OUTPUT</u>

Header record:

READ( ) *latitude, longitude, UA identifier, SF identifier, OS identifier, Version*

```
FORMAT (2(2X,A8),8X,'  UA_ID: ',A8,'  SF_ID: ',A8,'  OS_ID: ',A8,
        5X,'VERSION: ',I5)
```

where	*latitude*	=	latitude specified in Stage 3 of AERMET
	longitude	=	longitude specified in Stage 3 of AERMET
	UA identifier	=	station identifier for upper air data; usually the WBAN number used to extract the data from an archive data set
	SF identifier	=	station identifier for hourly surface observations; usually the WBAN number used in extracting the data
	OS identifier	=	on-site identifier
	Version	=	version date of AERMET used to generate file

Data records:

READ( ) *year, month, day, j_day, hour,* H, u_*, w_*, *VPTG,* Z_{ic}, Z_{im}, L, z_o, B_o, r, W_s, W_d, z_{ref}, *temp,* z_{temp}

```
FORMAT (3(I2,1X), I3,1X, I2,1X, F6.1,1X, 2(F6.3,1X), F5.0,1X, F8.1,1X, F5.2,1X,
        2(F6.2,1X), F7.2,1X, F5.0, 3(1X,F6.1))
```

where *j_day* = Julian date

H	=	sensible heat flux (W/m^2)
u_*	=	surface friction velocity (m/s)
w_*	=	convective velocity scale (m/s)
VPTG	=	vertical potential temperature gradient in the 500 m layer above PBL
Z_{ic}	=	height of convectively-generated boundary layer (m)
Z_{im}	=	height of mechanically-generated boundary layer (m)
L	=	Monin-Obukhov length (m)
z_o	=	surface roughness length (m)
B_o	=	Bowen ratio
r	=	Albedo
W_s	=	wind speed (m/s)
W_d	=	wind direction (degrees)
z_{ref}	=	reference height for W_s and W_d (m)
temp	=	temperature (K)
z_{temp}	=	reference height for *temp* (m)

The sensible heat flux, Bowen ratio and albedo are not used by AERMOD, but are passed through by AERMET for information purposes only.

<u>PROFILE</u>

READ( ) *year, month, day , hour, height, top,* WD*nn*, WS*nn*, TT*nn*, SA*nn*, SW*nn*

FORMAT (4(I2,1X), F6.1,1X, I1,1X, F5.0,1X, F7.2,1X, F7.1, 1X,F6.1, 1X,F7.2)

where	*height*	=	measurement height (m)
	top	=	1, if this is the last (highest) level for this *hour*, or 0 otherwise
	WD*nn*	=	wind direction at the current level (degrees)
	WS*nn*	=	wind speed at the current level (m/s)
	TT*nn*	=	temperature at the current level (°C)
	SA*nn*	=	σ_θ (degrees)
	SW*nn*	=	σ_w (m/s)

D.2 THRESHOLD VIOLATION FILES (MAXIFILE OPTION)

The OU MAXIFILE card for the AERMOD model allows the user the option to generate a file or files of threshold violations for specific source group and averaging period combinations. The file consists of several header records, each identified with an asterisk (*) in column one. The header information includes the model name and version number, the first line of the title information for the run, the list of modeling option keywords applicable to the results, the averaging period and source group included in the file, and the threshold value. Any value equal to or exceeding the threshold value will be included in the file. The header also includes the format used for writing the data records, and column headers for the variables included in the file. The variables provided on each data record include the averaging period, the source group ID, the date (YYMMDDHH) for the end of averaging period, the X and Y coordinates of the receptor location, receptor terrain elevation, hill height scale, flagpole receptor height, and the concentration value that violated the threshold. The following example from a threshold file identifies the contents of the MAXIFILE:

```
* AERMOD (02222): A Simple Example Problem for the AERMOD Model with PRIME
* MODELING OPTIONS USED:
*  CONC                              FLAT
*         MAXI-FILE FOR  3-HR VALUES >= A THRESHOLD OF    50.00
*         FOR SOURCE GROUP: ALL
*         FORMAT: (1X,I3,1X,A8,1X,I8.8,2(1X,F13.5),3(1X,F7.2),1X,F13.5)
*AVE   GRP     DATE           X             Y        ZELEV   ZHILL   ZFLAG  AVERAGE CONC
*___ ________ ________  ____________  ____________  ______  ______  ______  ____________
   3 ALL      88030112     344.68271     -60.77686    0.00    0.00    0.00       67.83944
   3 ALL      88030112     492.40387     -86.82408    0.00    0.00    0.00       68.92943
   3 ALL      88030112     164.44621     -59.85352    0.00    0.00    0.00      114.30801
```

D.3 POSTPROCESSOR FILES (POSTFILE OPTION)

The OU POSTFILE card for the AERMOD model allows the user the option of creating output files of concurrent concentration values suitable for postprocessing. The model offers two options for the type of file generated - one is an unformatted file, and the other is a formatted file of X, Y, CONC values suitable for inputting to plotting programs.

The unformatted POSTFILE option generates a separate unformatted data record of concurrent values for each averaging period and source group specified. The averaging period and source group combinations may be written to separate files, or combined into a single file. Each record begins with the date variable for the end of the averaging period (an integer variable of the form YYMMDDHH), the averaging period (e.g., an integer value of 3 for 3-hour averages), and the source group ID (eight characters). Following these three header variables, the record includes the concentration values for each receptor location, in the order in which the receptors are defined on the RE pathway. The results are output to the unformatted file or files as they are calculated by the model.

The formatted plot file option for the POSTFILE keyword includes several lines of header information, each identified with an asterisk (*) in column one. The header information includes the model name and version number, the first line of the title information for the run, the list of modeling option keywords applicable to the results, the averaging period and source group included in the file, and the number of receptors included. The header also includes the format used for writing the data records, and column headers for the variables included in the file. The variables provided on each data record include the X and Y coordinates of the receptor location, the concentration value for that location, receptor terrain elevation, hill height scale, flagpole receptor height, the averaging period, the source group ID, and the either the date variable for the end of the averaging period (in the form of YYMMDDHH) for short term averages or the number of hours in the period for PERIOD averages. The following example from a formatted postprocessor file for PERIOD averages identifies the contents of the POSTFILE:

```
* AERMOD (02222): A Simple Example Problem for the AERMOD Model with PRIME
* MODELING OPTIONS USED:
*  CONC                                FLAT
*         POST/PLOT FILE OF PERIOD VALUES FOR SOURCE GROUP: ALL
*         FOR A TOTAL OF   144 RECEPTORS.
*         FORMAT: (3(1X,F13.5),3(1X,F8.2),2X,A6,2X,A8,2X,I8.8,2X,A8)
*        X            Y      AVERAGE CONC    ZELEV    ZHILL    ZFLAG    AVE     GRP      NUM HRS   NET ID
*  ___________  ___________  ___________  _______  _______  _______  ______  ________  ________  ________
      30.38843     172.34135      0.12122     0.00     0.00     0.00  PERIOD  ALL       00000096  POL1
      60.77686     344.68271      0.40298     0.00     0.00     0.00  PERIOD  ALL       00000096  POL1
      86.82409     492.40387      0.72628     0.00     0.00     0.00  PERIOD  ALL       00000096  POL1
     173.64818     984.80774      1.19873     0.00     0.00     0.00  PERIOD  ALL       00000096  POL1
      59.85352     164.44621      0.12341     0.00     0.00     0.00  PERIOD  ALL       00000096  POL1
     119.70705     328.89243      0.54534     0.00     0.00     0.00  PERIOD  ALL       00000096  POL1
     171.01007     469.84631      1.15766     0.00     0.00     0.00  PERIOD  ALL       00000096  POL1
     342.02014     939.69263      2.35508     0.00     0.00     0.00  PERIOD  ALL       00000096  POL1
      87.50000     151.55444      0.12574     0.00     0.00     0.00  PERIOD  ALL       00000096  POL1
     175.00000     303.10889      0.51807     0.00     0.00     0.00  PERIOD  ALL       00000096  POL1
```

D.4 HIGH VALUE RESULTS FOR PLOTTING (PLOTFILE OPTION)

The OU PLOTFILE card for the AERMOD model allows the user the option of creating output files of highest concentration values suitable for importing into graphics software to generate contour plots. The formatted plot files generated by the PLOTFILE include several lines of header information, each identified with an asterisk (*) in column one. The header information includes the model name and version number, the first line of the title information for the run, the list of modeling option keywords applicable to the results, the averaging period and source group included in the file, the high value (e.g. 2ND highest) included for plotting, and the number of receptors included. The header also includes the format used for writing the data records, and column headers for the variables included in the file. The variables provided on each data record include the X and Y coordinates of the receptor location, the concentration value for that location, receptor terrain elevation, hill height scale, flagpole receptor height, averaging period, the source group ID, and either the high value included for short term averages or the number of hours in the period for PERIOD averages. For short term averages, the PLOTFILE also includes the date variable for the end of the averaging period (in the form of YYMMDDHH). The PERIOD average PLOTFILE uses the same format for the data records as the PERIOD average formatted POSTFILE shown in the previous section. The following example from a plot file for high second highest 24-hour averages identifies the contents of the PLOTFILE:

```
* AERMOD (02222): A Simple Example Problem for the AERMOD Model with PRIME
* MODELING OPTIONS USED:
*  CONC                                FLAT
*         PLOT FILE OF  HIGH 2ND  HIGH 24-HR VALUES FOR SOURCE GROUP: ALL
*         FOR A TOTAL OF   144 RECEPTORS.
*         FORMAT: (3(1X,F13.5),3(1X,F8.2),3X,A5,2X,A8,2X,A4,6X,A8)
*        X            Y      AVERAGE CONC    ZELEV    ZHILL    ZFLAG    AVE     GRP       HIVAL    NET ID
* ___________  ___________  ____________  ________  ________  ________  ______  ________  ________  ______
     30.38843    172.34135       0.20960      0.00      0.00      0.00  24-HR  ALL       2ND       POL1
     60.77686    344.68271       0.53718      0.00      0.00      0.00  24-HR  ALL       2ND       POL1
     86.82409    492.40387       0.92291      0.00      0.00      0.00  24-HR  ALL       2ND       POL1
    173.64818    984.80774       0.95650      0.00      0.00      0.00  24-HR  ALL       2ND       POL1
     59.85352    164.44621       0.19456      0.00      0.00      0.00  24-HR  ALL       2ND       POL1
    119.70705    328.89243       0.53717      0.00      0.00      0.00  24-HR  ALL       2ND       POL1
    171.01007    469.84631       0.92291      0.00      0.00      0.00  24-HR  ALL       2ND       POL1
    342.02014    939.69263       0.95650      0.00      0.00      0.00  24-HR  ALL       2ND       POL1
     87.50000    151.55444       0.19213      0.00      0.00      0.00  24-HR  ALL       2ND       POL1
    175.00000    303.10889       0.53711      0.00      0.00      0.00  24-HR  ALL       2ND       POL1
```

The PLOTFILE output also includes a flag ('**') identifying the receptor with the highest concentration. For short term averages, the flag precedes the date field. For period averages, the

flag precedes the field with the number of hours in the period.

D.5 TOXX MODEL INPUT FILES (TOXXFILE OPTION)

The OU TOXXFILE card for the AERMOD model allows the user the option to generate an unformatted file or files of threshold violations for a specific averaging period for use with the TOXX model component of TOXST. The file consists of three header records, including the first line of the title information for the run, the number of source groups, receptors and averaging periods, information on the type of receptor network, and the threshold cutoff value. Following the header records are pairs of records identifying the specific averaging period, source group and receptor location and corresponding concentration value for the values exceeding the user-specified threshold. If any source group exceeds the threshold for a given averaging period and receptor location, then the concentrations for all source groups are output for that period and receptor. The structure of the unformatted file for the AERMOD model TOXXFILE option is described below:

Record #	Description
1	Title (80 characters)
2	IYEAR, NUMGRP, NUMREC, NUMPER, ITAB, NXTOX, NYTOX, IDUM1, IDUM2, IDUM3
3	CUTOFF, RDUM1, ..., RDUM9

where: TITLE = First line of title (80 characters)
IYEAR = Year of simulation
NUMGRP = No. of source groups
NUMREC = Total no. of receptors
NUMPER = No. of averaging periods (e.g., number of hours in the year)
ITAB = 1 for polar grid; 2 for Cartesian grid; 0 for discrete receptors or mixed grids
NXTOX = No. of x-coordinates (or distances) in receptor network
NYTOX = No. of y-coordinates (or directions) in receptor network
IDUM1, IDUM2, IDUM3 = dummy integer variables, arbitrarily set equal to zero
CUTOFF = User-specified threshold for outputting results (g/m^3)
RDUM1, ..., RDUM9 = Dummy real variables (nine) arbitrarily set equal to zero

Following the header records, the file consists of pairs of records including an ID variable

identifying the data period, source group number and receptor number, and the corresponding concentration values. The number of values included in each record is controlled by the NPAIR PARAMETER, which is initially set at 100 in MODULE MAIN1. The identification variable is determined as follows:

IDCONC = IPER*100000 + IGRP*1000 + IREC

where:
- IPER = the hour number for the year corresponding to the concentration value
- IGRP = the source group number (the order in which the group was defined on the SO pathway)
- IREC = the receptor number (the order in which the receptor was defined on the RE pathway)

D.6 MAXIMUM VALUES BY RANK (RANKFILE OPTION)

The OU RANKFILE card for the AERMOD model allows the user the option of creating output files of the maximum concentration values by rank, suitable for generating Q-Q or quantile plots. The data contained in the RANKFILE output is based on the MAXTABLE arrays, except that only one occurrence per data period is included. The formatted data files generated by the RANKFILE include several lines of header information, each identified with an asterisk (*) in column one. The header information includes the model name and version number, the first line of the title information for the run, the list of modeling option keywords applicable to the results, the averaging period included in the file, and the number of ranked values included. The header also includes the format used for writing the data records, and column headers for the variables included in the file. The variables provided on each data record include the rank, concentration value, X and Y coordinates of the receptor location, receptor terrain elevation, hill height scale, flagpole receptor height, and the source group ID. Each RANKFILE includes results for all of the source groups for a particular averaging period. Since the RANKFILE only include one occurrence per data period, the file may not include the number of ranked values requested, especially for evaluation data bases of limited duration. The following example identifies the contents of the RANKFILE:

```
* AERMOD (02222): A Simple Example Problem for the AERMOD Model with PRIME
* MODELING OPTIONS USED:
*  CONC                                FLAT
*         RANK-FILE OF UP TO    40 TOP  3-HR VALUES FOR     1 SOURCE GROUPS
*         INCLUDES OVERALL MAXIMUM VALUES WITH DUPLICATE DATA PERIODS REMOVED
*         FORMAT: (1X,I3,1X,F13.5,1X,I8.8,2(1X,F13.5),3(1X,F7.2),2X,A8)
*RANK AVERAGE CONC   DATE          X             Y        ZELEV   ZHILL   ZFLAG     GRP
*____ ____________ ________  ____________  ____________  ______  ______  ______  ________
   1     335.81046 88030112     433.01270    -250.00000    0.00    0.00    0.00  ALL
   2     329.29599 88030115     469.84631    -171.01007    0.00    0.00    0.00  ALL
   3     111.95577 88030118     433.01270    -250.00000    0.00    0.00    0.00  ALL
   4      71.34813 88030312     433.01270    -250.00000    0.00    0.00    0.00  ALL
   5      45.24860 88030215     342.02014     939.69263    0.00    0.00    0.00  ALL
```

D.7 ARC-MAXIMUM VALUES FOR EVALUATION (EVALFILE OPTION)

The OU EVALFILE card for the AERMOD model allows the user the option of creating output files of the arc-maximum concentration values for individual sources suitable for use in model evaluation studies. The data contained in the EVALFILE output is based on the maximum value along arcs of receptors, identified using the RE EVALCART card. Receptors may be grouped on arcs based on their distance from the source, or other logical grouping. The formatted EVALFILE output includes five records of information for each selected source and each hour of meteorological data. The information provided is as follows:

Record 1:
- Source ID (eight characters)
- Date variable (YYMMDDHH)
- Arc ID (eight characters)
- Arc maximum χ/Q
- Emission rate for arc maximum (including unit conversions)
- Crosswind integrated concentration based on true centerline concentration
- Normalized non-dimensional crosswind integrated concentration

Record 2:
- Downwind distance corresponding to arc maximum (m)
- Effective wind speed corresponding to arc maximum (m/s)
- Effective σ_v corresponding to arc maximum (m/s)
- Effective σ_w corresponding to arc maximum (m/s)
- σ_y corresponding to arc maximum (m)
- Effective plume height corresponding to arc maximum (m)

Record 3:
- Monin-Obukhov length for current hour (m)
- Mixing height for current hour (m)
- Surface friction velocity for current hour (m/s)
- Convective velocity scale for current hour if unstable (m/s), or
  σ_z for current hour if stable (m)

Buoyancy flux for current hour (m^4/s^3)
Momentum flux for current hour (m^4/s^2)

Record 4: Bowen ratio for current hour
Plume penetration factor for current hour
Centerline χ/Q for direct plume
Centerline χ/Q for indirect plume
Centerline χ/Q for penetrated plume
Nondimensional downwind distance

Record 5: Plume height/mixing height ratio
Non-dimensional buoyancy flux
Source release height (m)
Arc centerline χ/Q
Developmental option settings place holder (string of 10 zeroes)
Flow vector for current hour (degrees)
Effective height for stable plume reflections (m)

The following Fortran WRITE and FORMAT statements are used to write the results to the EVALFILE output:

```
      WRITE(IELUNT(ISRC),9000) SRCID(ISRC), KURDAT, ARCID(I),
     &                         ARCMAX(I), QMAX(I), CWIC, CWICN,
     &                         DXMAX(I), UOUT, SVMAX(I),
     &                         SWMAX(I), SYOUT, HEMAX(I),
     &                         OBULEN, ZI, USTAR, PWSTAR, FB, FM,
     &                         BOWEN, PPF, CHIDML(I), CHINML(I), CHI3ML(I),
     &                         XNDIM, HEOZI, FSTAR, AHS(ISRC), ARCCL(I),
     &                         AFV, HSBLMX(I)

9000  FORMAT(1X,A8,1X,I8,1X,A8,4(1X,G12.6),
     &       /,9X,6(1X,G12.4),/,9X,6(1X,G12.4),
     &       /,9X,6(1X,G12.4),/,9X,4(1X,G12.4),1X,'0000000000',
     &       1X,G12.4,1X,G12.4)
```

D.8 RESULTS BY SEASON AND HOUR-OF-DAY (SEASONHR OPTION)

The SEASONHR option is used to output a file containing the average results by season and hour-of-day. The formatted data files generated by the SEASONHR option include several lines of header information, each identified with an asterisk (*) in column one. The header information includes the model name and version number, the first line of the title information for the run, the list of modeling option keywords applicable to the results, the source group included in the file, and the number of receptors. The header also includes the format used for writing the

data records, and column headers for the variables included in the file. The variables provided on each data record include the X and Y coordinates of the receptor location, the average concentration value, receptor terrain elevation, hill height scale, flagpole receptor height, source group ID, number of non-calm and non-missing hours used to calculate the season-by-hour-of-day averages (the NHRS column), season index (the SEAS column with 1 for winter, 2 for spring, 3 for summer, and 4 for fall), and the hour-of-day for the concentration value. A sample from a SEASONHR output file is shown below:

```
* AERMOD (02222): A Simple Example Problem for the AERMOD Model with PRIME
* MODELING OPTIONS USED:
*  CONC                                FLAT
*         FILE OF SEASON/HOUR VALUES FOR SOURCE GROUP: ALL
*         FOR A TOTAL OF   144 RECEPTORS.
*         FORMAT: (2(1X,F13.5),1(1X,F13.8),3(1X,F7.2),2X,A8,2X,3(I4,2X),A8)
*   X           Y      AVERAGE CONC   ZELEV   ZHILL   ZFLAG   GRP    NHRS  SEAS  HOUR  NET ID
* _______  _________  ___________  ______  ______  ______  ______  ____  ____  ____  ________
  30.38843  172.34135    0.01390196    0.00    0.00    0.00    ALL     4     2     1    POL1
```

APPENDIX E.

QUICK REFERENCE FOR AERMOD

CO Keywords	Type	Parameters	Section
TITLEONE	M-N	Title1	3.2.1
TITLETWO	O-N	Title2	3.2.1
MODELOPT	M-N	DFAULT CONC FLAT NOSTD NOCHKD NOWARN SCREEN TOXICS SCIM	3.2.2
AVERTIME	M-N	Time1 Time2 Time3 Time4 MONTH PERIOD ANNUAL	3.2.3
URBANOPT	O-N	UrbPop (UrbName) (UrbRoughness)	3.2.4
POLLUTID	M-N	Pollut	3.2.5
HALFLIFE	O-N	Haflif	3.2.6
DCAYCOEF	O-N	Decay	3.2.6
FLAGPOLE	O-N	(Flagdf)	3.2.7
RUNORNOT	M-N	RUN or NOT	3.2.8
EVENTFIL	O-N	(Evfile) (Evopt)	3.2.9
SAVEFILE	O-N	(Savfil) (Dayinc) (Savfl2)	3.2.10
INITFILE	O-N	(Inifil)	3.2.10
MULTYEAR	O-N	H6H Savfil (Inifil)	3.2.11
DEBUGOPT	O-N	MODEL (Dbgfil) and/or METEOR (Dbmfil)	3.2.13
ERRORFIL	O-N	(Errfil)	3.2.14

SO Keywords	Type	Parameters	Section
ELEVUNIT	O-N	METERS or FEET	3.3
LOCATION	M-R	Srcid Srctyp Xs Ys (Zs) (Srctyp = POINT, VOLUME, or AREA)	3.3.1
SRCPARAM	M-R	Srcid Ptemis Stkhgt Stktmp Stkvel Stkdia (POINT Source) Vlemis Relhgt Syinit Szinit (VOLUME Source) Aremis Relhgt Xinit (Yinit) (Angle) (Szinit) (AREA Source) Aremis Relhgt Nverts (Szinit) (AREAPOLY source) Aremis Relhgt Radius (Nverts) (Szinit) (AREACIRC source)	3.3.2
BUILDHGT	O-R	Srcid (or Srcrng) Dsbh(i),i=1,Nsec	3.3.3
BUILDWID	O-R	Srcid (or Srcrng) Dsbw(i),i=1,Nsec	3.3.3
XBADJ	O-R	Srcid (or Srcrng) Xbadj(i),i=1,Nsec	3.3.3
YBADJ	O-R	Srcid (or Srcrng) Ybadj(i),i=1,Nsec	3.3.3
AREAVERT	O-R	Srcid Xv(1) Yv(1) Xv(2) Yv(2) ... Xv(i) Yv(i)	3.3.2
URBANSRC	O-R	Srcid's and/or Srcrng's	3.3.4
EMISFACT	O-R	Srcid (or Srcrng) Qflag Qfact(i),i=1,Nqf	3.3.5
EMISUNIT	O-N	Emifac Emilbl Conlbl	3.3.6
HOUREMIS	O-R	Emifil Srcid's Srcrng's	3.3.9
INCLUDED	O-R	Incfil	3.3.10
SRCGROUP	M-R	Grpid Srcid's Srcrng's	3.3.11

Type: M - Mandatory N - Non-repeatable
O - Optional R - Repeatable

RE Keywords	Type	Parameters	Section
ELEVUNIT	O-N	METERS or FEET	3.4
GRIDCART	O-R	Netid STA XYINC Xinit Xnum Xdelta Yinit Ynum Ydelta, or XPNTS Gridx1 Gridx2 Gridx3 ... GridxN, and YPNTS Gridy1 Gridy2 Gridy3 ... GridyN ELEV Row Zelev1 Zelev2 Zelev3 ... ZelevN HILL Row Zhill1 Zhill2 Zhill3 ... ZhillN FLAG Row Zflag1 Zflag2 Zflag3 ... ZflagN END	3.4.1
GRIDPOLR	O-R	Netid STA ORIG Xinit Yinit, or ORIG Srcid DIST Ring1 Ring2 Ring3 ... RingN DDIR Dir1 Dir2 Dir3 ... DirN, or GDIR Dirnum Dirini Dirinc ELEV Rad Zelev1 Zelev2 Zelev3 ... ZelevN HILL Rad Zhill1 Zhill2 Zhill3 ... ZhillN FLAG Rad Zflag1 Zflag2 Zflag3 ... ZflagN END	3.4.1
DISCCART	O-R	Xcoord Ycoord (Zelev Zhill) (Zflag)	3.4.3
EVALCART	O-R	Xcoord Ycoord Zelev Zhill Zflag Arcid (Name)	3.4.3
DISCPOLR	O-R	Srcid Range Direct (Zelev Zhill) (Zflag)	3.4.3
INCLUDED	O-R	Incfil	3.4.4

Note: While all RE keywords are optional, at least one receptor must be defined for each run.

ME Keywords	Type	Parameters	Section
SURFFILE	M-N	Sfcfil (Format)	3.5.1
PROFFILE	M-N	Profil (Format)	3.5.1
SURFDATA	M-N	Stanum Year (Name) (Xcoord Ycoord)	3.5.2
UAIRDATA	M-N	Stanum Year (Name) (Xcoord Ycoord)	3.5.2
SITEDATA	O-N	Stanum Year (Name) (Xcoord Ycoord)	3.5.2
PROFBASE	M-N	BaseElev (Units)	3.5.3
STARTEND	O-N	Strtyr Strtmn Strtdy (Strthr) Endyr Endmn Enddy (Endhr)	3.5.4
DAYRANGE	O-R	Range1 Range2 Range3 ... RangeN	3.5.4
SCIMBYHR	O-N	NRegStart NRegInt NWetStart NWetInt (SfcFilnam PflFilnam)	3.5.7
WDROTATE	O-N	Rotang	3.5.5
WINDCATS	O-N	Ws1 Ws2 Ws3 Ws4 Ws5	3.5.6

EV Keywords	Type	Parameters	Section
EVENTPER	M-R	Evname Aveper Grpid Date	3.6.1
EVENTLOC	M-R	Evname XR= Xr YR= Yr (Zelev) (Zflag) or RNG= Rng DIR= Dir (Zelev) (Zflag)	3.6.2

OU Keywords	Type	Parameters	Section
RECTABLE	O-R	Aveper FIRST SECOND ... SIXTH or 1ST 2ND ... 6TH	3.7.1
MAXTABLE	O-R	Aveper Maxnum	3.7.1
DAYTABLE	O-N	Avper1 Avper2 Avper3 Avper4	3.7.1
MAXIFILE	O-R	Aveper Grpid Thresh Filnam (Funit)	3.7.2
PLOTFILE	O-R	Aveper Grpid Hivalu Filnam (Funit) Aveper Grpid Filnam (Funit) (PERIOD or ANNUAL ave)	3.7.2 3.7.2
POSTFILE	O-R	Aveper Grpid Format Filnam (Funit)	3.7.2
RANKFILE	O-R	Aveper Hinum Filnam (Funit)	3.7.2
EVALFILE	O-R	Srcid Filnam (Funit)	3.7.2
TOXXFILE	O-R	Aveper Cutoff Filnam (Funit)	3.7.2
SEASONHR	O-R	GroupID Filenam (Funit)	3.7.2
EVENTOUT	M-N	SOCONT or DETAIL (Applies for EVENT processing only)	3.7.3

GLOSSARY

AERMAP -- AMS/EPA Regulatory Model (AERMOD) Terrain Preprocessor.

AERMET -- AMS/EPA Regulatory Model (AERMOD) Meteorological Preprocessor.

AERMOD -- AMS/EPA Regulatory Model.

ASCII -- American Standard Code for Information Interchange, a standard set of codes used by computers and communication devices. Sometimes used to refer to files containing only such standard codes, without any application-specific codes such as might be present in a document file from a word processor program.

CD-144 Format -- Card Deck-144 data format available from NCDC for National Weather Service surface observations commonly used for dispersion models. Each record represents an 80-column "card image".

CO -- **CO**ntrol, the 2-character pathway ID for input runstream images used to specify overall job control options.

CO Pathway -- Collective term for the group of input runstream images used to specify the overall job control options, including titles, dispersion options, terrain options, etc.

Directory -- A logical subdivision of a disk used to organize files stored on a disk.

Dispersion Model -- A group of related mathematical algorithms used to estimate (model) the dispersion of pollutants in the atmosphere due to transport by the mean (average) wind and small scale turbulence.

DOS -- Disk Operating System. Software that manages applications software and provides an interface between applications and the system hardware components, such as the disk drive, terminal, and keyboard.

Echo of inputs -- By default, the AERMOD model will echo the input runstream images, character by character, into the main printed output file. This serves as a record of the inputs as originally entered by the user, without any rounding of the numerical values. The echoing can be suppressed with the NO ECHO option.

EOF -- End-of-File.

EPA -- U. S. Environmental Protection Agency.

Error message -- A message written by the model to the error/message file whenever an error is encountered that will inhibit data processing.

Error/Message File -- A file used for storage of messages written by the model.

EV -- **EV**ent, the 2-character pathway ID for input runstream images used to specify event inputs for the Short Term EVENT model.

EV Pathway -- Collective term for the group of input runstream images used to specify the event periods and location for the Short Term EVENT model.

EVENT Processing -- An option in the AERMOD model specifically designed to provide source contribution (culpability) information for specific events of interest, e.g., design values or threshold violations.

Extended Memory -- Additional memory on 80386 and 80486 PCs that allows programs to address memory beyond the 640 KB limit of DOS. Special software is required to utilize this extra memory.

Fatal Error -- Any error which inhibits further processing of data by the model. Model continues to read input images to check for errors during setup, and will continue to read input meteorological data during calculation phase.

Flow Vector -- The direction towards which the wind is blowing.

GMT -- Greenwich Mean Time, the time at the 0° meridian.

Informational Message -- Any message written to the error/message file that may be of interest to the user, but which have no direct bearing on the validity of the results, and do not affect processing.

Input Image -- User supplied input, read through the default input device, controlling the model options and data input. A single card or record from the input runstream file. Each input image consists of a pathway ID (may be blank indicating a continuation of the previous pathway), a keyword (may also be blank for continuation of a keyword), and possibly one or more parameter fields.

Input Runstream File -- The basic input file to the AERMOD model controlling the modeling options, source data, receptor locations, meteorological data file specifications, and output options. Consists of a series of input images grouped into functional pathways.

Julian Day -- The number of the day in the year, i.e., Julian Day = 1 for January 1 and 365 (or 366 for leap years) for December 31.

KB -- Kilobyte, 1000 bytes, a unit of storage on a disk

Keyword -- The 8-character codes that follow immediately after the pathway ID in the input run stream data.

LST -- Local Standard Time.

Math Co-processor -- A computer chip used to speed up floating point arithmetic in a personal computer.

MB -- Megabyte, one million bytes, a unit of storage on a disk

ME -- **ME**teorology, the 2-character pathway ID for input runstream images used to specify meteorological data options

ME Pathway -- Collective term for the group of input runstream images used to specify the input meteorological data file and other meteorological variables, including the period to process from the meteorological file for the AERMOD model.

Meteorological Data File -- Any file containing meteorological data, whether it be mixing heights, surface observations or on-site data.

Missing Value -- Alphanumeric character(s) that represent breaks in the temporal or spatial record of an atmospheric variable.

Mixing Height -- The depth through which atmospheric pollutants are typically mixed by dispersive processes.

NCDC -- National Climatic Data Center, the federal agency responsible for distribution of the National Weather Service upper air, mixing height and surface observation data.

NO ECHO -- Option to suppress echoing of the runstream input images to the main printed output file.

NWS -- National Weather Service.

On-site Data -- Data collected from a meteorological measurement program operated in the vicinity of the site to be modeled in the dispersion analysis.

OU -- **OU**tput, the 2-character pathway ID for input runstream images used to specify output options.

OU Pathway -- Collective term for the group of input runstream images used to specify the output options for a particular run.

Overlay -- One or more subprograms that reside on disk and are loaded into memory only when needed.

Pasquill Stability Categories -- A classification of the dispersive capacity of the atmosphere, originally defined using surface wind speed, solar insolation (daytime) and cloudiness

(nighttime). They have since been reinterpreted using various other meteorological variables.

Pathway -- One of the six major functional divisions in the input runstream file for the AERMOD model. These are **CO**ntrol, **SO**urce, **RE**ceptor, **ME**teorology, **EV**ent, and **OU**tput (see these entries in this section for a description).

PC -- Personal Computer, a wide ranging class of computers designed for personal use, typically small enough to fit on a desktop.

Quality Assessment -- Judgment of the quality of the data.

Quality Assessment Check -- Determining if the reported value of a variable is reasonable (see also Range Check).

Quality Assessment Message -- Message written to the error/message file when a data value is determined to be suspect.

Quality Assessment Violation -- Occurrences when data values are determined to be suspect (see also Range Check Violation).

RAM -- Random Access Memory on a personal computer.

RAMMET -- Meteorological processor program used for regulatory applications capable of processing twice-daily mixing heights (TD-9689 format) and hourly surface weather observations (CD-144 format) for use in dispersion models such as AERMOD, CRSTER, MPTER and RAM.

Range Check -- Determining if a variable falls within predefined upper and lower bounds.

Range Check Violation -- Determination that the value of a variable is outside range defined by upper and lower bound values (see also Quality Assessment Violation).

RE -- **RE**ceptor, the 2-character pathway ID for input runstream images used to specify receptor locations.

RE Pathway -- Collective term for the group of input runstream images used to specify the receptor locations for a particular run.

Regulatory Applications -- Dispersion modeling involving regulatory decision-making as described in the Guideline on Air Quality Models, which is published as Appendix W of 40 CFR Part 51 (as revised).

Regulatory Model -- A dispersion model that has been approved for use by the regulatory offices of the EPA, specifically one that is included in Appendix A of the Guideline on Air Quality Models, (as revised), such as the AERMOD model.

Runstream File -- Collectively, all input images required to process input options and input data for the AERMOD model.

SCRAM -- Support Center for Regulatory Air Models - part of EPA's website on the internet, used by EPA for disseminating air quality dispersion models, modeling guidance, and related information.

Secondary Keyword -- A descriptive alphabetical keyword used as a parameter for one of the main runstream keywords to specify a particular option.

SO -- **SO**urce, the 2-character pathway ID for input runstream images used to specify input source parameters and source groups.

SO Pathway -- Collective term for the group of input runstream images used to specify the source input parameters and source group information.

Station Identification -- An integer or character string used to uniquely identify a station or site as provided in the upper air (TD-5600 and TD-6201), mixing height (TD-9689), and surface weather (CD-144 and TD-3280) data formats available from NCDC. There are no standard station numbers for on-site data or card image/screening data, and the user may include any integer string

Subdirectory -- A directory below the root, or highest level, directory or another subdirectory, used for organization of files on a storage medium such as a PC hard disk.

Surface Weather Observations -- A collection of atmospheric data on the state of the atmosphere as observed from the earth's surface. In the U.S. the National Weather Service collect these data on a regular basis at selected locations.

Surface Roughness Length -- Height at which the wind speed extrapolated from a near-surface wind speed profile becomes zero.

Syntax -- The order, structure and arrangement of the inputs that make of the input runstream file, specifically, the rules governing the placement of the various input elements including pathway IDs, keywords, and parameters.

TD-1440 Format -- A format available from NCDC for summarizing NWS surface observations in an 80-column format; the CD-144 format is a subset of this format. This format has been superseded by the TD-3280 format.

TD-3280 Format -- The current format available from NCDC for summarizing NWS surface weather observations in an elemental structure, i.e., observations of a single atmospheric variable are grouped together for a designated period of time.

TD-5600 Format -- A format available from NCDC for reporting NWS upper air sounding data. This format has been superseded by the TD-6201 format.

TD-6201 Format -- The current format available from NCDC for reporting NWS upper air data. The file structure is essentially the same as the TD-5600 format except that there is more quality assurance information.

TD-9689 Format -- The format available from NCDC for mixing heights estimated from morning upper air temperature and pressure data and hourly surface observations of temperature.

Unformatted File -- A file written without the use of a FORTRAN FORMAT statement, sometimes referred to as a binary file.

Upper Air Data (or soundings) -- Meteorological data obtained from balloon- borne instrumentation that provides information on pressure, temperature, humidity, and wind away from the surface of the earth.

Vertical Potential Temperature Gradient -- The change of potential temperature with height, used in modeling the plume rise through a stable layer, and indicates the strength of the stable temperature inversion. A positive value means that potential temperature increases with height above ground and indicates a stable atmosphere.

Warning Message -- A message written by the model to the error/message file whenever a problem arises that <u>may</u> reflect an erroneous condition, but does not inhibit further processing.

TECHNICAL REPORT DATA

(Please read Instructions on reverse before completing)

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4. TITLE AND SUBTITLE User's Guide for the AMS/EPA Regulatory Model- AERMOD		5. REORT DATE September 2004 6. PERFORMING ORGANIZATION CODE
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15. SUPPLEMENTARY NOTES

16. ABSTRACT This User's Guide for the AMS/EPA Regulatory Model (AERMOD) provides user instructions for the AERMOD model. The technical description of the AERMOD algorithms is provided in a separate document. The revised AERMOD model described in this user's guide includes the following modifications and enhancements: the PRIME building downwash algorithms based on the ISC-PRIME model; use of allocatable arrays for data storage; incorporation of EVENT processing for analyzing short-term source culpability; post-1997 PM10 processing; a non-regulatory default TOXICS option that includes optimizations for area sources and the Sampled Chronological Input Model (SCIM) option; explicit treatment of multiple-year meteorological data files and the ANNUAL average; and options to specify emissions that vary by season, hour-of-day and day-of-week.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
AERMOD, user's guide, air dispersion model,	Air Pollution models	
18. DISTRIBUTION STATEMENT Release Unlimited	19. SECURITY CLASS *(Report)* Unclassified 20. SECURITY CLASS *(Page)* Unclassified	21. No of pages 227 22. PRICE free

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RULE 803. PREVENTION OF SIGNIFICANT DETERIORATION. (Adopted 4/17/1997)

A. Applicability

The purpose of Prevention of Significant Deterioration is to provide for the review of new and modified stationary sources of air pollution and provide mechanisms by which Authorities to Construct such sources may be granted without interfering with the protection of areas designated attainment or unclassifiable.

Prevention of Significant Deterioration requirements shall apply to all new stationary sources and all modifications to existing stationary sources which, after construction emit or may emit any attainment pollutants. Stationary sources which emit or may emit precursors to nonattainment pollutants shall, in addition to the requirements of Nonattainment Review, be subject to the increment protection provisions contained within the Prevention of Significant Deterioration requirements; including Section F (Modeling), G (Pre and Post Construction Monitoring), (Visibility, Soils, and Vegetation Analysis), G.2 (Protection of Class I Areas) and I (Ambient Air Quality Standards and Air Quality Increments).

B. Exemptions

1. This Rule shall not apply to prescribed burning of forest, agriculture or range land, road construction or any other non-point source, common to timber harvesting or agricultural practices.

C. Definitions

See Rules 102 and 801 for definitions applicable to this Rule.

D. Requirements -- Best Available Control Technology

1. An applicant shall apply Best Available Control Technology to a new source or modification of an existing source, for any net emissions increases of any attainment pollutant which is equal to or greater that any emission level shown in Table 1. In addition, an applicant shall apply Best Available Control Technology to a new source or modification of an existing major stationary source or major modification, for any net emissions increase which would construct within 10 kilometers of a Class I area and have an impact on such area equal to or greater than 1 microgram per cubic meter (24-hour average).

Table 1 - PSD Best Available Control Technology & Modelling Thresholds

Pollutant	Pounds/day	Tons/year
Particulate Matter	120	--
PM_{10} and its precursors	80	--
Carbon Monoxide	550	--
NO_x, SO_x, and ROCs	120	--
Lead	3.28	--
Asbestos	0.04	--
Beryllium	0.0022	--
Mercury	0.55	--
Vinyl Chloride	5.48	--
Fluorides	16.4	--
Sulfuric Acid Mist	38.4	--
Total Reduced Sulfur (including H_2S)	54.8	--
Reduced sulfur compounds	54.8	--
Municipal waste combustor organics	--	0.0000035
Municipal waste combustor metals	--	15
Municipal waste combustor acid gases	--	40
All other attainment pollutants or precursors	120	--

2. For any stationary source subject to this Rule, Best Available Control Technology shall be an emission limitation based on the maximum degree of reduction for each pollutant which would be emitted from any new or modified stationary source, which on a case-by-case basis, taking into account energy, environmental, and economic impacts and other costs, is achievable for such source or modification through application of production processes or available methods, systems, and techniques, including fuel cleaning or treatment or innovative fuel combustion techniques for control of such pollutant. In no event shall application of Best Available Control Technology result in emissions which would exceed the emissions allowed under the applicable New Source Standards of Performance.

E. Requirements - Emission Offsets

1. Offset Requirement, General

a. Offsets shall be actual, average quarterly enforceable emission reductions from existing sources sufficient to offset all anticipated quarterly emission increases, as calculated according to Section J. of this Rule, associated with a new or modified stationary source and which will result in a net air quality benefit.

b. In areas other than Class I areas or Class I impact areas, offsets as specified in E.2 below shall be required for any attainment pollutant or total suspended particulates for a new or modified stationary source with a net emissions increase exceeding 240 pounds per day, for reactive organic compounds, nitrogen oxides, sulfur oxides, total suspended particulates, or PM_{10}.

2. Location of Offsets and Offset Ratios

Net emissions increases from a proposed new or modified source subject to this Rule, which is to be located outside a Class I area or Class I impact area, are to be offset with emissions reductions from within a 15 mile radius of the proposed source. The offset ratio shall be 1.2 to 1 for reductions in emissions located outside of the proposed source but within the 15 mile radius, and the Control Officer shall analyze the impact on the air quality increment.

a. If an applicant demonstrates to the satisfaction of the Control Officer that sufficient offsets do not exist at sources owned by the applicant, and are not available at other sources within a 15 mile radius of the proposed source, offsets shall be obtained from an upwind area, within the air basin at a ratio as specified by the Control Officer, and the Control Officer shall analyze the impact on the air quality increment.

b. If an applicant demonstrates to the satisfaction of the Control Officer that sufficient offsets do not exist at sources owned by the applicant, and are not available at other sources within the 15 mile radius of the proposed source, or within the upwind portion of the air basin, offsets shall be obtained from an upwind area, outside the air basin at a ratio and distance based on an air quality analysis sufficient to demonstrate that no air quality increment will be exceeded.

C. If an applicant demonstrates to the satisfaction of the Control Officer that sufficient offsets do not exist at sources owned by the applicant and are not available at other sources within a 15 mile radius or in an upwind area, the Control Officer may choose to allow an applicant to use a portion of the remaining air quality increment.

F. Requirements - Air Quality Impact Analysis: Modeling

1. The applicant for a new or modified stationary source which will have a net emissions increase of any attainment pollutant which is equal to or greater than any amount specified in Table 1 shall demonstrate, by Air Quality Impact Analysis, to the satisfaction of the Control Officer through use of air quality models meeting the requirements of Section K(3) (Air Quality Models) and Rule 805 (Air Quality Impact Analysis) that their emissions will cause no ambient air quality standard or increment to be exceeded. In addition, the Control Officer may require an Air Quality Impact Analysis for any new or modified stationary source that the Control Officer has determined has the potential to cause or contribute to a violation of an air quality standard or consume the maximum allowable increment increase.

2. The applicant for a new or modified stationary source which emits in its entirety more than 20 pounds per hour of any attainment pollutant or total suspended particulates shall demonstrate to the satisfaction of the Control Officer through use of air quality models meeting the requirements of Section K(3) (Air Quality Models) and Rule 805 (Air Quality Impact Analysis that their emissions will cause no ambient air quality standard or increment to be exceeded.

3. If a new or modified source will impact a Class I Area, the applicant shall analyze the stationary source's impact on air quality related values for those values which the Federal Land Manager has identified.

G. Requirements - Air Quality Impact Analysis: Pre and Post Construction Monitoring

1. The owner or operator of a new or modified stationary source which will have a net emissions increase of more than any emission level shown in Table 2 of any other attainment pollutant shall conduct ambient air quality monitoring with pre-construction monitoring not less than one year in duration. New non-major stationary sources or modifications can be exempt from this

requirement if the Control Officer finds that there will be sufficient data available to determine the effects that the emissions from the stationary source or modification may have, or are having on air quality in the area. New major stationary sources and major modifications must comply with the pre-construction monitoring requirement unless the Control Officer finds that there will be sufficient data available to determine the effects that the emissions from the stationary source or modification may have, or are having, on air quality, in the area; and if the applicant can demonstrate to the satisfaction of the Control Officer that the new major source or major modification impacts less than those listed in 40 CFR 52.21(I)(8). Post construction monitoring shall be required until such time as the Control Officer determines the effects emissions from the stationary source or modification may have. All monitoring shall comply with Environmental Protection Agency guidelines (see 40 CFR 58, Appendix B) and other instructions of the Control Officer.

Table 2: Prevention of Significant Deterioration Monitoring Thresholds

Pollutant	Pounds/day
Particulate Matter	120
PM_{10}	80
All other attainment pollutants	240

2. Protection of Class I Areas

Any net emissions increase of less than 120 pounds per day of an attainment pollutant or total suspended particulates, except PM_{10}, which is 80 pounds per day, or 15 tons per year, associated with a stationary source emitting over 100 tons per year of any attainment pollutant which would construct within a Class I or Class I impact area and would increase ambient pollutant concentration within the Class I area by one microgram per cubic meter (24 hour average) or more shall be subject to monitoring.

H. Requirements - Visibility, Soils, and Vegetation Analysis

For a new or modified stationary source which emits, in its entirety, more than any emission level shown in Table 2 of any attainment pollutant, the applicant shall provide the Control Officer with analysis of impairment to visibility, soils, and vegetation that would occur as a result of the source or modification and general commercial, industrial, and other growth associated with the source or modification.

I. Requirements - Ambient Air Quality Standards and Air Quality Increments

1. In no case shall the emissions from the new or modified stationary source cause the violation of an ambient air quality standard or lead to the violation of any air quality increment. The provisions contained in Rule 805, shall be used to estimate the effects of a new or modified source. In making this determination the Control Officer shall take into account the mitigation of emissions through offsets obtained pursuant to this Rule.

2. The applicant may consume the full increment range, where noted in Table 3, if the applicant enters into a Memorandum of Agreement with the District providing for alternative mitigation. The cost of such mitigation shall not exceed $333 per year per microgram/m^3 over the lower level of the increment range for this pollutant based on the maximum modeled concentration of the first

year of operation of the stationary source, and thereafter based on the single actual worst case contribution by the stationary source to monitored concentrations during the previous year. If post-construction monitoring shows no consumption beyond the lower level of the increment range for any period of three consecutive years after the year of peak projected emissions, then no further monitoring or mitigation shall be required for the purposes of this sub-section. If, subsequent to the termination of monitoring or mitigation, the APCD determines that consumption has increased beyond the lower level of the increment range, District may require reinstatement of post-construction monitoring or mitigation. As an alternative to monitoring-based mitigation costs, the applicant may choose, with consent of the District, to base the maximum cost of mitigation for the first year on the maximum modeled concentration of the projected peak emissions year, thereafter depreciating this amount by 10 percent per year over 10 years or the life of the project, whichever is less. The District's consent shall not be unreasonably withheld provided that the 10 year depreciation schedule results in an equitable, realistic approximation of the applicant's projected annual emission rate. Cost of mitigation during the final year of the project shall be prorated to reflect the portion of the year during which the facility is in operation.

This increment and mitigation requirement shall be reviewed if the Air Resources Board or Environmental Protection Agency develop an increment or other alternative with supporting technical rationale.

Baseline air quality shall be the ambient concentration level reflecting actual air quality as monitored or modeled as of the existing baseline date shown in the air quality increments table, minus any contribution attributable to emissions from major stationary sources and modifications (as defined in 40 CFR 52.21(b) as it existed on 8-7-80) constructed since January 6, 1975.

Table 3 - AIR QUALITY INCREMENTS

Pollutant: Monitoring Level	Maximum Allowable Increase (in micrograms/cubic meter) Class I	Class II	Baseline Date	Air Quality Standard
Total Suspended Particulates:				
Annual Geometric Mean	5	19	8-7-77	
24-Hour Maximum	10	37		
Sulfur Dioxide:				
Annual Arithmetic Mean	2	20	8-7-77	80
24-Hour Maximum	5	91	8-7-78	365
3-Hour Maximum	25	512	8-7-78	1,300~~0~~
Nitrogen Oxides:				
Annual Arithmetic Mean	2.5	25	2-8-88	100
1-Hour Maximum[1,*]	10	100 to 470	1-1-84	470
Carbon Monoxide:				
8-Hour Maximum	200	2500	1-1-84	10,000
1-Hour Maximum[1]	800	10000	1-1-84	40,000
Reactive Organic Compounds[1]:				
3-Hour Maximum*	3	40-160	1-1-84	
Particulate Matter (<10 μm):				
Annual Arithmetic Mean	4	17	8-7-77	50
24-Hour Maximum	8	30	8-7-77	150
24-Hour Maximum[1,*]		12-30	1-1-84	50

* The applicant may consume the full increment range pursuant to the requirements of Section I.2.

1 Not a federal increment.

J. Requirements - Calculations

1. The maximum design capacity (potential to emit) of a new stationary source or modification shall be used to determine the emissions from the new source or modification. However, the applicant may agree to federally enforceable limitations on the operation of the new source or modification. If those limitations are included in both Authorities to Construct and Permits to Operate issued according to the Rule, then those limitations shall be used to establish the emissions from the new source or modifications.

2. The emissions from an existing source shall be based on the actual operating conditions of the existing source averaged over the three consecutive years immediately preceding the date of application, or such shorter period as may be applicable in cases where the existing source has not been in operation for three consecutive years. The Control Officer may approve any other time period of at least three years within five years prior to the date of application that is more representative of normal source operation. If violation of laws, rules, regulations, permit conditions, or orders of the District, the Air Resources Board, or the Environmental Protection

Agency occurred during the period used to determine the operating conditions, then adjustments to the operating conditions shall be made to determine the emissions the existing source would have caused without such violations.

3. The maximum net increase in quarterly (January through March, April through June, July through September, October through December) emissions from new stationary sources and modifications shall be offset by the average quarterly decrease in emissions from one or more existing sources, after this decrease has been reduced by the appropriate ratio in Section E.2.

K. Requirements - Administration

1. Air Quality Increment Analysis

The Control Officer shall evaluate the impact on the air quality increment of the emissions from the proposed source and any offsets obtained pursuant to Section F.2. (offset requirement). Any emissions from secondary emissions associated with the source shall be included in the determination of increment consumption.

2. Review of Air Quality Increment Consumption

The Control Officer shall assess the remaining air quality increment a minimum of once every five years. Should a stationary source subject to E.2. be cited, the frequency of assessment of the remaining air quality increment shall be every two years. The assessment of the remaining air quality increment shall be based on any changes in emissions including area sources and any changes in air quality background levels. For sulfur dioxide and particulate matter, the emissions from major stationary sources (as defined in 40 CFR 52.21(b) as it existed on 8-7-80) constructed since January 6, 1975 shall be included in air quality increment consumption. For nitrogen dioxide, the emissions from major stationary sources constructed since February 8, 1988 shall be included in air quality increment consumption. Within sixty days of a determination of an increment violation the District will initiate action to mitigate the violation.

3. Air Quality Models

All air quality models used for the purposes of this Rule shall be consistent with the requirements specified in Rule 805.D.1 for air quality models unless the Control Officer finds that such model is inappropriate for use. After making such finding the Control Officer may designate an alternate model only after allowing for public comment and only with concurrence of the Air Resources Board and the Environmental Protection Agency. All modeling costs associated with siting of a stationary source shall be borne by the applicant.

4. Permit Notice

The Control Officer shall provide a copy of the portion of the application dealing with the emissions and air quality impacts of a new source, for any permit application for a proposed major stationary source whose emissions would affect a Class I area, to the Federal Land Manager and the federal official charged with direct responsibility for management of the affected lands within 10 days of the determination that a Class I area will be impacted. The Federal Land Manager shall be notified within 10 days of all subsequent actions relating to the consideration of such Permit.

5. Preliminary Decision

Following acceptance of an application as complete, the Control Officer shall perform the evaluations required to determine compliance with this Rule and make a preliminary written decision as to whether an authority to construct should be approved, conditionally approved, or disapproved. The decision shall be supported by a succinct written analysis. The District shall transmit to the Air Resources Board its preliminary written decision and analysis for sources subject to E (Emission Offsets), F (Modeling), G.2. (Protection of Class I Areas), and I (Air Quality Increments) no later than the date of publication as required in Section K 6), below. For major sources, the District shall transmit to USEPA its preliminary written decision and analysis.

6. Publication and Public Comment

Within 10 days following a preliminary decision to approve or conditionally approve a permit pursuant to Sections E (Offsets) and G 2) (Protection of Class I Areas) of this Rule, Control Officer shall publish in at least one newspaper of general circulation in the District a public notice stating the preliminary decision of the Control Officer, noting how pertinent information can be obtained, and inviting written public comment for a 30-day period following the date of publication. The public notice will include notification of the opportunity for a public hearing and will indicate the anticipated degree of increment consumption. A public hearing may be called if sufficient interest is generated or if any aggrieved party so requests in writing within the 30-day comment period. After considering all comments, including those presented at any hearings held, the Control Officer will reach a decision and notify the appropriate parties.

7. Sources Impacting Class I Areas

The Control Officer shall accept, and consider comments offered within public comment period following date of publication, by the Federal Land Manager of any lands contained within a Class I area impacted by a proposed facility or modification. If the Federal Land Manager demonstrates that the emissions from a proposed facility or modification would have an adverse impact on the air quality-related values (including visibility) of any federal mandatory Class I areas, and if the Control Officer concurs with such demonstration, then the Control Officer shall deny the Authority to Construct.

8. Federal Land Manager Appeals

If the Control Officer issues an authority to construct with which the Federal Land Manager or the federal official charged with direct responsibility over the specified lands does not concur, the decision may be appealed to the Hearing Board.

9. Public Inspection

The Control Officer shall make available for public inspection at the District's office the information submitted by the applicant and the Control Officer's analysis no later than the time that notice of the preliminary decision is published, pursuant to Section K.5), above. Information submitted which contains trade secrets shall be handled in accordance with Section 6254.7 of the Government Code and relevant sections of the Administrative Code of the State of California. Further, all such information shall be transmitted, no later than the date of publication, to the Air Resources Board and the Environmental Protection Agency regional office, and to any party which requests such information at the current cost of mailing and duplication.

10. Authority to Construct, Final Action

Within the applicable time period specified in Rule 208, the Control Officer shall take final action on the application after considering all written comments. The Control Officer shall provide written notice of the final action to the applicant, the Environmental Protection Agency, and the Air Resources Board, and shall publish a notice of approval of the permit in a newspaper of general circulation and shall make the notice and all supporting documents available for public inspection at the District's office.

11. Requirements, Permit to Operate

As a condition for the issuance of a permit to operate, the Control Officer shall require that the new source or modification, and any sources which provide offsets, be operated in the manner assumed in making the analysis to determine compliance with this Rule, or as conditioned in the Authority to Construct. The Permit to Operate shall include specific emissions limitations which reflect Best Available Control Technology.

The operation of any source which provides offsets shall be subject to enforceable permit conditions, containing specific emissions limitations to ensure that the emission reductions will be provided in accordance with the provisions of this Rule and maintained throughout the operation of the new or modified source which is the beneficiary of the offsets. Where the source of offsets is not subject to a permit, a written contract shall be required between the applicant and the owner or operator of such source, which contract, by its terms, shall be enforceable by the Control Officer. The permit and contract shall be submitted to the Air Resources Board to be forwarded to the Environmental Protection Agency as part of the State Implementation Plan. A violation of the emission limitation provisions of any such contract shall be chargeable to the applicant.

12. Issuance, Permit to Operate

The Control Officer shall issue a Permit to Operate a stationary source subject to the requirements of this Rule if it is determined that any offsets required as a condition of an Authority to Construct or amendment to a Permit to Operate will commence not later than the initial operation of the new or modified source, and that the offsets shall be maintained throughout the operation of the new or modified source which is the beneficiary of the offsets. Further, the Control Officer shall determine that all conditions specified in the Authority to Construct have been or will be complied with by any dates specified. Conditions which have not been met at the time the Permit to Operate is issued shall be incorporated into the Permit to Operate. Where a new or modified stationary source is, in whole or in part, a replacement for an existing stationary source on the same property, the Control Officer may allow a maximum 90 days as a start-up period for simultaneous operation of the existing stationary source and the new source or replacement.

Nevada Bureau of Air Pollution Control
Ambient Air Quality Monitoring Guidelines

The Nevada Ambient Air Quality Monitoring Guidelines are prepared for facilities required by air quality permit restriction to conduct ambient air quality monitoring. These guidelines are provided in the interest of obtaining valid, consistent, usable data from required ambient monitoring operations within the State of Nevada. Deviations from or alternatives to the guideline procedures or requirements shall be submitted to the Bureau of Air Pollution Control, prior to their use, for review and approval.

References

To ensure data of sufficiently high quality, all sampling and continuous monitoring for Prevention of Significant Deterioration (PSD) permitting use, or as the result of a PSD permit condition to monitor, shall be conducted in accordance with these guidelines and the applicable guidance and procedures published by the U.S. Environmental Protection Agency (EPA). Sampling and continuous monitoring for non-PSD permitting use, or as the result of a non-PSD permit condition to monitor, shall be conducted according to these guidelines and published EPA guidance and procedures for State and Local Air Monitoring Stations (SLAMS). After one year of PSD monitoring conducted subsequent to the commencement of operation of a PSD facility, the PSD facility required to monitor as a PSD permit condition may conduct SLAMS, rather than PSD, monitoring, if continued monitoring is required. However, only PSD monitoring will be sufficient to support applications for new and revised PSD permits. Modeling applications may require meteorological data collected in accordance with the "On-Site Meteorological Program Guidance for Regulatory Modeling Applications" (updated as the "Meteorological Monitoring Guidance for Regulatory Modeling Applications").

Several EPA documents follow that contain information to be adhered to in the operation of such monitoring networks. These documents and their titles may be revised at times.

> "Code of Federal Regulations," Title 40, Chapter I, Subchapter C, Part 58, Ambient Air Quality Surveillance. This reference is available for purchase from the Superintendent of Documents, Attn: New Orders, P.O. Box 371954, Pittsburgh, PA 15250-7954, telephone (202) 512-1800. It may also be available at Internet address www.epa.gov/docs/epacfr40/chapt-I.info/subch-C/40P0058.pdf.
>
> "Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD)," EPA-450/4-87-007, US EPA Office of Air Quality Planning and Standards (OAQPS), Research Triangle Park (RTP), NC 27711. A copy of this document is available for purchase from the National Technical Information Service (NTIS), stock number PB 90-168030, telephone (800) 553-6847. It may also be available at Internet address www.epa.gov/ttn/amtic/files/ambient/criteria/reldocs/4-87-007.pdf.

"On-Site Meteorological Program Guidance for Regulatory Modeling Applications," EPA-450/4-87-013, OAQPS, RTP, NC 27711. This meteorological guidance document is available for purchase from the NTIS, stock number PB 87-227542, telephone (800) 553-6847. An updated version entitled "Meteorological Monitoring Guidance for Regulatory Modeling Applications," EPA-454/R-99-005, may be available at Internet address www.epa.gov/scram001/guidance/guide/mmgrma.pdf.

"Quality Assurance Handbook for Air Pollution Measurement Systems, Volume I, a Field Guide to Environmental Quality Assurance," EPA-600/R-94/038a, US EPA Office of Research and Development (ORD), Washington, DC 20460. See the ordering information below for the EPA-600-series documents. It may also be available at Internet address www.epa.gov/ttnamti1/files/ambient/qaqc/r94-038a.pdf.

"Quality Assurance Handbook for Air Pollution Measurement Systems, Volume II: Part 1," EPA-454/R-98/004, OAQPS, Research Triangle Park, NC 27711. This document is available for purchase from the NTIS, stock number PB 99-129876, telephone (800) 553-6847. It may also be available at Internet address www.epa.gov/ttnamti1/files/ambient/qaqc/redbook.pdf.

"Quality Assurance Handbook for Air Pollution Measurement Systems, Volume II, Ambient Air Specific Methods (Interim Edition)," EPA-600/R-94/038b, ORD, Washington, DC 20460. See the ordering information below for the EPA-600-series documents. The section of Volume II of greatest interest to most operators is Section 2.11, the "Reference Method for the Determination of Particulate Matter as PM_{10} in the Atmosphere (High-Volume PM_{10} Sampler Method)." A more recent version of this document with minor updates is known as the "Quality Assurance Guidance Document 2.11, Monitoring PM_{10} in Ambient Air Using a High-Volume Sampler Method." This more recent PM_{10} guidance document may only be available on the Internet. An address at which this document may be found is www.epa.gov/ttn/amtic/files/ambient/qaqc/2-11meth.pdf.

"Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements," EPA-600/R-94/038d, ORD, Washington, DC 20460. See the ordering information below for the EPA-600-series documents. A more recent version of this document (EPA-600/R95/050) is available for purchase from the NTIS, stock number PB 95-199782, telephone (800) 553-6847. It may also be available at Internet address www.epa.gov/clariton/clhtml/pubord.html.

The EPA-600-series documents, Volumes I, II and IV of the Quality Assurance Handbook for Air Pollution Measurement Systems, should be available at no cost from the US EPA National

Service Center for Environmental Publications (NSCEP), telephone (800) 490-9198 or (513) 569-7562.

Discussion

The Bureau of Air Pollution Control monitoring requirements specifically include the following:

1) All meteorological data collected shall be recovered at a minimum rate of 90% of the total data possible on an annual basis for each variable being measured.
2) All ambient monitoring data for pollutants (including data from continuous analyzers and manual samplers) shall be recovered at a minimum rate of 80% of the total data possible per continuous analyzer or manual sampler per calendar quarter for PSD monitoring, or at a minimum rate of 75% of the total data possible per continuous analyzer or manual sampler per calendar quarter for non-PSD (SLAMS) monitoring.
3) For meteorological monitoring data, at least 30 minutes of valid observations are required to represent an hourly average. If 15-minute averages are used for compiling meteorological data, then at least two valid 15-minute periods are required for an hourly average. For continuous ambient air quality monitoring data, at least 45 minutes of valid observations are required to represent an hourly average. Running averages of more than one hour shall require valid observations for at least 75 percent of the hours in the averaging period. All invalid data observations shall be excluded from the average.
4) The EPA specification for the high-volume particulate sampling run time is 24 hours ± one hour (1440 minutes ± 60 minutes), from midnight to midnight, local time.
5) The EPA specification for the TSP high-volume particulate sampling flow rate is 39 to 60 actual cubic feet per minute (not corrected to standard conditions).
6) The EPA specification for the PM_{10} high-volume particulate sampling flow rate is 1.02 to 1.24 actual cubic meters per minute, or 36 to 44 actual cubic feet per minute (not corrected to standard conditions).
7) For gaseous analyzers, the results of zero, span and precision checks shall be reported quarterly. Hourly instrument panel or instrument rack temperature shall be reported for gaseous analyzers. When an analyzer is operated outside the temperature range for which the analyzer is certified by the EPA, it may be necessary to invalidate the data, as described in the Quality Control and Quality Assurance section of these guidelines.

All required ambient air quality and meteorological monitoring data shall be submitted to the Bureau on a calendar quarter basis no later than sixty (60) days after the end of the applicable quarter. Should any of the requirements for a monitoring program not be maintained at the requisite levels, part or all of the data recovered may be deemed incomplete and may not be usable to support the environmental evaluation, ambient concentration assessment, or meteorological assumptions necessary for new or modified air quality permits, and the facility may be subject to noncompliance penalties for violations of its air quality permit restrictions.

Gaseous Analyzers

The limit at which continuous gaseous data shall be invalidated is the greater of 15 percent span drift or 15 ppb (1.5 ppm for carbon monoxide) zero drift.

For continuous analyzers, the same data sampling frequency is recommended as is required for meteorological monitoring. This sampling frequency of at least 360 samples per averaging period is met by electronically sampling the instrument output at least once every 10 seconds for hourly averages or at least once every 2.5 seconds for 15-minute averages. A sampling frequency of once every two seconds is recommended. The data sampling frequency shall be reported in the quarterly report. Data recovery shall be based on the total number of hours in the reporting period, not the number of hours possible less time used for quality control, upset conditions, etc.

Data shall be reported in a format suitable for comparison with the State ambient air quality standards. This includes reporting running averages, as applicable. Data recovery is based on one-hour averages.

Particulate Samplers

The data reported for high-volume particulate samplers shall include:

- sampler identification
- run date
- filter serial number
- elapsed run time (minutes)
- actual flow rate (m^3/min)
- standard flow rate (m^3/min)
- gross filter weight (g)
- tare filter weight (g)
- net weight (g)
- particulate concentration ($\mu g/m^3$)

For co-located particulate samplers, the particulate data for both samplers shall be reported in order to provide a precision check of the samplers. Sampling shall conform with the EPA national every-sixth-day particulate sampling schedule. A copy of the schedule is available from the Bureau upon request. Each sampler shall be operated at least every designated sixth day throughout the year. Any deviations from these scheduled run days require justification and written approval from the Bureau.

The most common type of sampler is the high-volume PM_{10} sampler; therefore, this guidance is directed toward high-volume PM_{10} samplers. PM_{10} may be measured by drawing a known volume of ambient air at a specified flow rate through a size-selective inlet and through a

quartz fiber filter. Particles in the PM_{10} size range are collected on the filter during a 24-hour sampling period from midnight to midnight, local time. After a period of equilibration for temperature and humidity, filters are weighed prior to and after collection of the sample to determine the net mass of the collected sample. The concentration of PM_{10} in the ambient air is computed as the total mass of the collected particles divided by the volume of air sampled. The reference method for PM_{10} sampling is given in 40 CFR Part 50, Appendix J and implemented in the "Quality Assurance Handbook for Air Pollution Measurement Systems, Volume II," Section 2.11 and in the "Quality Assurance Guidance Document 2.11, Monitoring PM_{10} in Ambient Air Using a High-Volume Sampler Method."

Co-located PM_{10} samplers are required on one or more sites in each facility's PM_{10} monitoring network, depending on the size of the network, in order that the precision of the samples from the network may be determined relative to EPA and Bureau requirements. The co-located samplers must be of the same type with the same inlet type and use the same method of flow control. The two samplers must be located within four meters of each other, but at least two meters apart to preclude any air flow interference. The vertical placement of the samplers must be such that the inlets are no lower than two meters and no higher than fifteen meters above ground elevation. If the sampler is to be located on a roof or near any structures, there must be a minimum clearance of two meters from surrounding walls or obstacles. Adjacent buildings or obstacles should be avoided so that the distance between an obstacle and the sampler is at least twice the height that the obstacle protrudes above the sampler. Also, there must be a minimum of a 270-degree arc of unrestricted airflow around each sampler. The predominant wind direction for the season of greatest pollutant concentration potential from the facility must be included in the 270-degree arc. Calibration, sampling and analysis must be the same for both co-located samplers and any other samplers in the sampling network to which the co-located samplers apply. One of the two co-located samplers must be designated as the primary or official sampler and the second designated as the secondary or duplicate sampler. The official sampler shall be used to report the air quality for the monitoring site and the duplicate sampler shall be used to determine the precision of the measurement. In the event of a failure of the official sampler, the duplicate sampler may be used to report the air quality for the monitoring site.

The measured concentrations from both co-located samplers shall be reported, as well as the percentage difference in concentrations between the two samplers for concentrations above 80 $\mu g/m^3$. With proper PM_{10} sampling and analysis, co-located samplers should generally be capable of precision of not more than seven percent difference for concentrations above 80 $\mu g/m^3$ and not more than five $\mu g/m^3$ difference for concentrations below 80 $\mu g/m^3$.

The accuracy of high-volume PM_{10} samplers is assessed by auditing the flow rate of each sampler with an orifice transfer standard. Then the corrected sampler flow rate without an orifice transfer standard is compared to the design flow rate.

The monitoring site location shall be representative of the point of maximum PM_{10}

concentration from the proposed and existing facilities at the limit of public access. This shall be determined based on the combined effect of existing facilities and the proposed new facility or modification. The maximum concentration at the point of public access may be determined through the use of an EPA-approved model. In the case where a model may not be applicable, the initial monitoring site location, supported by detailed maps, may be proposed by the applicant, and shall be based on atmospheric drainage and prevailing wind direction in the area where the facility is to be located. Sampler locations shall also satisfy the requirement to sample ambient air. Ambient air is defined in 40 CFR Part 50.1 (e) as "that portion of the atmosphere, external to buildings, to which the general public has access," and in the Nevada Administrative Code (NAC) 445B.018 as "that portion of the atmosphere which is external to buildings, structures, facilities, or installations to which the general public has access." Each monitoring site location shall be approved by Bureau staff.

Calculations for High-Volume PM_{10} Sampling

High-volume PM_{10} sampling calculations shall conform to the "Quality Assurance Guidance Document 2.11, Monitoring PM_{10} in Ambient Air Using a High-Volume Sampler Method" or Section 2.11 of the "Quality Assurance Handbook for Air Pollution Measurement Systems, Volume II, Ambient Air Specific Methods (Interim Edition)." This method utilizes sampler and orifice calibration relationships based on linear regressions involving the actual flow rate in the independent variable and the adjusted flow rate indicator reading in the dependent variable. Since the multiplier and exponent from a power-fit orifice certification ($y = ax^b$) are not usable in the specified PM_{10} calculations, power-fit orifice certifications shall be converted to linear-fit orifice certifications ($y = mx + b$) as shown in Section 2.11.2 of the Section 2.11 guidance documents.

Meteorological Data

Current on-site meteorological data are required for input to dispersion models used for analyzing the potential impacts from the air pollution sources at a facility. Dispersion modeling may be used to determine impacts from proposed facilities, proposed modifications to facilities, and for compliance determinations in the event of an exceedance. Meteorological data may be used to aid the Bureau in determining the source of a pollutant that has caused an exceedance of the standards and to aid a facility in correcting a problem.

Although only hourly averages of meteorological parameters are required to be reported to the Bureau, it may be advisable to collect and archive meteorological data in 15-minute averages, while reporting hourly averages. For example, new dispersion models being developed by the EPA for evaluating air quality impacts may require the use of 15-minute averages.

The minimum meteorological data sampling frequency of 360 samples per averaging period is met by electronically sampling equipment output at least once every 10 seconds for hourly averages or at least once every 2.5 seconds for 15-minute averages. A sampling frequency of once

every two seconds is recommended. A sampling frequency of at least once every 2.5 seconds is required for dataloggers that utilize 15-minute averages to calculate sigma theta according to the Yamartino method, as discussed below. The data sampling frequency shall be reported in the quarterly report.

Data recovery shall be based on the total number of hours in the reporting period, not the number of hours possible less time used for quality control, upset conditions, etc. To conform to common modeling requirements, hourly meteorological data shall be reported for the period ending at the hour (i.e., the data between midnight and one o'clock shall be reported for hour "one"). The hourly average values shall be stored and reported for each parameter as follows:

Year, Julian Day, Hour, Wind Speed (m/s), Wind Direction (degrees clockwise from true north), Temperature (K or C), Sigma Theta, or,
YY (or YYYY) JJJ HH SS.SS DDD.D TTT.T VV.VV.

Meteorological data shall be recorded to an electronic medium, approved by the Bureau, in the format indicated above (space-delineated or comma-delineated string, ASCII file) and be accompanied by a "Read Me" text file explaining the order of meteorological data entries and definitions of units for data entries. The Bureau currently prefers 3.5-inch diskettes in IBM-compatible format. The meteorological data are to be processed such that the fields for all parameters are right-justified. A missing or invalid meteorological datum value shall be identified as a field of nines (9's).

The data recovery for each meteorological parameter shall be identified in the hardcopy quarterly report. It is not necessary to report hourly meteorological data in hardcopy.

The preferred method for calculating sigma theta (σ_Θ), the standard deviation of the horizontal wind direction, is the Yamartino method described in Section 6, Meteorological Data Processing, of the "On-Site Meteorological Program Guidance for Regulatory Modeling Applications" or the "Meteorological Monitoring Guidance for Regulatory Modeling Applications." The use of other methods to calculate σ_Θ requires prior Bureau approval.

The following formulas are employed by the Yamartino method:

$$\sigma_{\Theta} = \arcsin(\varepsilon)\ [\ 1 + 0.1547\,\varepsilon^{3}\ ],$$

where

$$\varepsilon = \sqrt{1 - \{\ [\ \overline{\sin(\Theta_i)}\ ]^2 + [\ \overline{\cos(\Theta_i)}\ ]^2\ \}}$$

and Θ_i is defined as the horizontal wind direction, measured clockwise from north with values restricted from 001 to 360 degrees, inclusive. To minimize the effects of meander under light wind speed conditions on σ_{Θ} for the hour, it is recommended that four 15-minute values be computed and averaged as follows:

$$\sigma_{\Theta}\ (1-\mathrm{hr}) = \sqrt{\left(\sigma_{\Theta_{15}}{}^{2} + \sigma_{\Theta_{30}}{}^{2} + \sigma_{\Theta_{45}}{}^{2} + \sigma_{\Theta_{60}}{}^{2}\right)/4}$$

Quality Control and Quality Assurance

The results of particulate, gaseous and meteorological performance audits called for in the References section above shall be reported to the Bureau with the monitoring report for the calendar quarter in which the audits were conducted. For meteorological monitoring, a performance audit for each parameter is required twice yearly at each site, every other quarter. A performance audit for each ambient air quality (pollutant) automated analyzer and manual sampler is required to be conducted quarterly for PSD monitoring and for non-PSD monitoring with not more than one automated analyzer or manual sampler for a pollutant. The minimum audit schedule for non-PSD monitoring with more than one automated analyzer or manual sampler for a pollutant is the same as for SLAMS monitoring, as presented in 40 CFR Part 58, Appendix A, Section 3.

Particulate Sampling

For high-volume PM_{10} sampling, copies shall be submitted each calendar quarter of the most recent orifice transfer standard certifications for both calibration and audit orifices, with the slope, intercept and correlation coefficient for each orifice calculated according to Section 2.11.2 of the "Quality Assurance Guidance Document 2.11, Monitoring PM_{10} in Ambient Air Using a High-Volume Sampler Method" or Section 2.11 of the "Quality Assurance Handbook for Air Pollution Measurement Systems, Volume II, Ambient Air Specific Methods (Interim Edition)." Also copies shall be submitted each calendar quarter of the audit sheets and sampler calibration sheets applicable to the report quarter, calculated according to Sections 2.11.7 and 2.11.2 of the Section 2.11 guidance documents, showing the following:

- ambient temperature

- uncorrected station atmospheric pressure
- orifice pressure drop
- sampler pressure or sampler pressure indicator reading
- sampler calibration slope, intercept and correlation coefficient.

Sample calibration sheets are shown in the Section 2.11 guidance documents, Figure 2.3 and Figure 2.5, respectively, for mass-flow-controlled (MFC) and volumetric-flow-controlled (VFC) high-volume samplers. Some versions of Section 2.11 guidance documents (e.g., the 1987 version and second draft September 1997 version) may contain an error on the MFC Sampler Calibration Data Sheet, Figure 2.3. There the formula for the subsequent calculation of the sampler flow rate with a flow recorder using a square root scale, such as a Dickson recorder with square root chart paper (the concentric circles become more widely spaced away from the center of the circular chart), may be in error. This formula should have "mean I" moved outside (to the left of) the left square root bracket, so that the square root applies only to $(T_{av} + 30)/P_{av}$ and not to "mean I." The correct formula is then:

$$\text{Ave. } Q_a = \{\text{mean I } [(T_{av} + 30)/P_{av}]^{1/2} - b\}\{1/m\}.$$

This error was recently corrected on the Internet copy of the September 1997 version.
Sample audit sheets are found in Figure 7.1 and Figure 7.3 for MFC and VFC samplers, respectively.

The filters shall be handled with care to minimize breakage and loss of sample. Unexposed and exposed filters shall be equilibrated in an environment with controlled temperature and humidity for at least 24 hours before weighing. The mean temperature shall be between 15°C and 30°C, with a variability of not more than ±3°C. The mean relative humidity shall be between 20 and 45 percent, with a variability of not more than ±5 percent. If filters must be weighed outside the conditioning chamber, begin the weighing within 30 seconds of removal of the filters. Filters shall be weighed on an analytical balance with a minimum resolution of 0.1 mg and a precision of 0.5 mg, that is calibrated at least annually. Before a batch of filters is weighed, the balance shall be zeroed according to the manufacturer's recommendations. The balance shall be checked at least daily during weighings for agreement within ±0.5 mg by weighing a pair of working mass reference standards with weights between 1g and 5 g. Each day of weighing, at least five exposed and unexposed filters per balance shall be reweighed. Each calendar quarter, a copy shall be submitted of the most recent balance calibration certification and the balance minimum resolution. Each calendar quarter, copies shall also be submitted of the records for each day of filter weighing, showing the equilibration temperature and relative humidity, results of weight checks with working mass reference standards, and results of exposed and unexposed filter reweighings.

Gaseous Monitoring

As applicable, for the quality control (station reference) and audit calibrators and gas

cylinders, submit copies each calendar quarter of the most recent certifications of the ozone generator calibrations, photometer calibrations, mass flow-controller calibrations, and gaseous standard concentrations with cylinder expiration dates.

Quality control for gaseous pollutant analyzers requires zero, span (±80% of full scale), and precision (80-100 ppb, or 8-10 ppm for carbon monoxide) checks at least every two weeks. The results of these checks shall be included in the quarterly report in the form of the known (calibrator or cylinder) input concentration and the analyzer response datalogger concentration for the zero, span and precision points. The accuracy tolerance for validating the data collected since the last satisfactory quality control check is a difference, or drift from true, of 15 percent of the concentration or 15 ppb (1.5 ppm for carbon monoxide), whichever is greater.

A recommended zero air circuit consists of the following scrubbers in the following order: first, a desiccant, such as silica gel; then, a carbon monoxide scrubber (if applicable), such as hopcalite; then an oxidant, such as Purafil (potassium permanganate); and last, a suitable grade of activated carbon. The desiccant should be first in the sequence so that dry air is delivered to the remaining scrubbers. The oxidant must precede the activated carbon, since it oxidizes nitric oxide to nitrogen dioxide, which is captured by the activated carbon. Otherwise, ambient nitric oxide may interfere with quality control and quality assurance for nitrogen dioxide and ozone monitoring.

The panel temperature, which is representative of the instrument rack air temperature, shall be monitored and reported quarterly as hourly averages, with the analyzer model and EPA-certified temperature range. Data collected outside the temperature range specified in the analyzer's EPA certification as a reference or equivalent method shall be evaluated in conjunction with other relevant information, such as the results of zero, span and precision checks conducted at similar panel temperature, and validated accordingly.

For ozone monitoring, test concentrations that rely on an ozone generator calibration, rather than a photometer concentration adjusted with pressure and temperature sensors, shall be derived from an ozone generator calibration done at the monitoring site elevation or mathematically corrected for the monitoring site elevation. Ozone generation shall be done at the same flow rate used to calibrate the ozone generator.

For nitrogen dioxide (NO_2) monitoring, required quality control checks and quality assurance audits shall use gas phase titration (GPT) or a permeation tube and record the NO_2 channel datalogger responses. Quality control checks of the nitric oxide (NO) and oxides of nitrogen (NO_x) channels alone are insufficient. Audit NO_2 concentrations using GPT shall be calculated from the drop in the true NO concentration with GPT. For the purpose of calculating NO_2 audit concentrations with GPT, the NO channel responses shall be adjusted to true NO concentrations by applying the NO channel audit linear regression slope and intercept to the NO channel readings before and after GPT. The subtraction difference between the adjusted NO concentrations before and after GPT is the true NO_2 audit concentration.

The NO_2 converter efficiency in percent is 100 times the slope of the linear regression, where the independent variable (x-value) is the drop in NO (adjusted to true concentration as described above) with gas phase titration, and the dependent variable (y-value) is the independent variable (x-value) less the drop in NO_x (adjusted to true concentration with the NO_x slope and intercept) with gas phase titration.

For this agency, gaseous multipoint audit results shall be evaluated by a linear regression analysis between the audit concentrations (x-axis) and the analyzer response datalogger concentrations (y-axis). Satisfactory audit results will exhibit a slope between 0.85 and 1.15, an intercept between -15 ppb and +15 ppb (between -1.5 ppm and +1.5 ppm for carbon monoxide), and a correlation coefficient between 0.9950 and 1.0000.

Certification

A statement shall accompany the ambient air monitoring results submitted to the Bureau that the information contained in the report is true and correct to the best of the knowledge of the responsible official, as defined in NAC 445B.156, signing and dating the statement.

Confidential Information

Pollutant monitoring data generally may not be kept confidential. Background pollutant monitoring data may not be kept confidential after they are used to support a regulatory decision, such as a decision whether to grant an air quality permit.

Tracy Price

From: "Jonathan Hill" <jhill@trinityconsultants.com>
To: "Tracy Price" <tprice3@mindspring.com>
Cc: "Maria Zufall" <MZufall@trinityconsultants.com>
Sent: Monday, October 08, 2007 3:33 PM
Subject: Re: viscreen

Tracy,

We have seen varying approaches in determining the worst-case winds for input to VISCREEN. It seems that the VISCREEN manual and VISCREEN tutorial themselves vary a bit in this interpretation. In the past, we have worked with Pete Courtney at Georgia EPD on VISCREEN applications and EPD seems to prefer the VISCREEN tutorial approach. For Santee Cooper's case specifically, we evaluated the wind frequencies for each year of the period and then selected the worst-case dispersion of those individual conditions (E stability, 5 m/s), similar to how the VISCREEN manual describes the procedure. Based on the spreadsheet tool that you sent, all 5 years of data were used in a single analysis, and that seems to yield a different, "worst-case" met condition of E stability, 3 m/s. We believe that there are many possible interpretations in this type of modeling, none necessarily more valid than another.

Best Regards,

Jon

Jon Hill
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Please Return to Tracy Price modeling Section.

"Tracy Price" <tprice3@mindspring.com>

10/05/2007 02:54 PM

Please take a look at these updates. We wou
stability for the viscreen runs.
Tracy Price, P.E.
SCDHEC/BAQ/Modeling Section
803-898-4466 (office) [Tu, Th - AM]
803-808-5735 (telecommute)[M, W, F - all (
priceto@dhec.sc.gov
BAQ - A "Best Workplace for Commuters"[
Jonathan Hill/Trinity Consultants] [attachme
Consultants] [attachment "SANTEE2.SUM"

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654 10-16-07

10/10/2007

Tracy Price

From: "Jonathan Hill" <jhill@trinityconsultants.com>
To: "Tracy Price" <tprice3@mindspring.com>
Cc: "Maria Zufall" <MZufall@trinityconsultants.com>
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"Tracy Price" <tprice3@mindspring.com>

10/05/2007 02:54 PM

To "Jon Hill" <jhill@trinityconsultants.com>
cc
Subject viscreen

Please take a look at these updates. We would like to know how you determined the wind speed and stability for the viscreen runs.
Tracy Price, P.E.
SCDHEC/BAQ/Modeling Section
803-898-4466 (office) [Tu, Th - AM]
803-808-5735 (telecommute)[M, W, F - all day; Tu, Th - PM]
priceto@dhec.sc.gov
BAQ - A "Best Workplace for Commuters"[attachment "Table 12 updated 10-5-2007.doc" deleted by Jonathan Hill/Trinity Consultants] [attachment "viscreen_tool_v1.0.xls" deleted by Jonathan Hill/Trinity Consultants] [attachment "SANTEE2.SUM" deleted by Jonathan Hill/Trinity Consultants]

Tracy Price

From: <Krivo.Stanley@epamail.epa.gov>
To: "Tracy Price" <tprice3@mindspring.com>
Cc: <Little.James@epamail.epa.gov>
Sent: Thursday, September 28, 2006 8:25 AM
Subject: Review Comments - Air Quality Modeling Santee Cooper

Tracy,

The following review comments on the Santee Copper Class I and Class II Area Air Quality Modeling Reports (dated July 2006) are provided for your use in reviewing these documents. If you have questions or additional information on any comment, I suggest we discuss these over the telephone.

Please note that because the air quality modeling reports available for review did include electronic modeling files, the modeling files have not been included in our review. Specific comments are provided separately for each document.

Class I Area Air Quality Modeling Report

1. Inventory of Other SO2 Sources – The inventory of other PSD SO2 emission sources included those located in other counties of SC and NC. The minor source baseline date that should be used to identify PSD affecting sources is that of the Class I area (i.e., receptor dependent). The following information is needed to ensure the appropriate PSD inventory was used in the modeling.
   - The Cape Romain PSD minor source baseline should be provided. Confirmation is needed that the Cape Romain minor source baseline date was used to develop the modeled inventory of other SO2 sources.
   - The bases (e.g., allowable, actual, etc.) of the emission rates provided in Table A-1 should be provided.

2. Federal Land Manager (FLM) Review – The FLM is responsible for the AQRV at the Cape Romain PSD Class I Area. Therefore, the FLM must be provided an opportunity to review and comment on this report. This is especially important because some of the impacts exceed acceptable thresholds. In addition, non-standard procedures were used in some of the analyses. For example:
   - Use of the 98th percentile rather than the largest visibility impact was used when evaluating the project's visibility impacts.
   - Use of the VISTAS' CALPOST processor for regional haze assessments rather than the IWAQM recommended Method 2.
   - Use of Method 6 as an alternate approach to for visibility assessment.
   - Use of the Rayleigh scattering value of 12 Mm-1 rather than the default value of 10 Mm-1.
   - Addition of sea-salt to the background concentrations.

3. Regulatory Version CALPUFF System – The EPA regulatory CALPUFF modeling system was not used in the assessment of PSD increments at Cape Romain. The following are the regulatory versions of each CALPUFF component.

CALPUFF - Version 5.511a
CALMET - Version 5.53a
CALPOST - Version 5.51

In addition, the regulatory default options should be used when performing the PSD increment assessment. Both the EPA regulatory CALPUFF model and the default options are available from the CALPUFF web site.
[Note: Although not used and required for the Class I area AQRV assessment, this same regulatory version of CALPUFF can be used for AQRV assessments.]

4. Meteorological Data – The VISTAS' three years of MM5 meteorological data were selected for the Class I area impact assessment; 2001 and 2002 at 12 km resolution, and 2003 at 36 km resolution. These basic meteorological data records were supplemented with the same surface and upper air observations that were used in VISTAS study. Given the 2-km resolution modeling domain and the availability of the selected meteorological data processed by VISTAS to 4-km resolution, use of meteorological data of 12 km and 36 km resolution does not appear appropriate.

5. CALSUM – The post utility program CALSUM was used to combine PSD increment consuming and expanding ambient concentrations. This post processing program does not appear in the CALPUFF web site. Further explanation and documentation is needed for this program.

6. Impact Analyses Results - The following comments are associated with the resultant impacts.
- The cumulative assessment of SO2 PSD increments reveals all concentrations less than the standards.
- Sulfur deposition values exceed the acceptable impact threshold. Adverse impact evaluation must be performed by the FLM.
- Nitrogen deposition values are less than the deposition impact threshold.
- Visibility results show maximum impacts exceeding the 5% threshold for all analysis scenarios. Adverse impact evaluation must be performed by the FLM.

Class II Area Air Quality Modeling Report

1. Project Emission Sources – The following comments are associated with the modeled project emission sources:
- The two 1,500 kW emergency generators and the fire pump were not included because they operate less than 500 hours per year. Table A-1 does not provide the emission rates for these sources.

The expected hourly emissions from these sources should be provided to better evaluate the appropriateness of not including these sources in the short-term impact assessments.
- The material handling emission sources with less than 1 lb/hr uncontrolled emissions were eliminated from the modeling. Review of Table A-1 reveals controlled emission rates for some of these sources comparable to, or larger than, material handling processes that were modeled (i.e., Limestone truck unloading, emergency reclaim hopper loading, and drop to crusher house and overland conveyors; Gypsum conveyor to stockout and truck unloading; Bottom ash transfer point; and Petcoke storage pile). These emission units should be included in the modeling.
- The bases for the emission estimates provided in Table 2-2 should be provided.
- The Table 2-2 hourly emission rates for SO2 and NOx are less than the values provided in Table A-1. Table 2-2 values appear only appropriate for 24-hour or longer averaging periods. The 3-hour short term SO2 standards should be modeled with the larger Table A-1 values.

2. Load Analysis – The report states that the types of sources included with this project are not expected to produce increased ambient impact with reduced operating loads. The report does not provide any demonstration or information to support this statement.

3. Ozone Assessment – Project VOC emissions exceed 100 TPY. Although the report correctly states that source-by-source ozone impacts are rarely modeled, the PSD permit application should still address the potential impact of project emissions on area ozone levels.

4. Pre-Construction Monitoring – The significance analysis modeling results provided in Table 3-2 show SO2, NO2, and PM10 concentrations greater than the de minimis monitoring levels. Therefore, pre-construction monitoring was addressed. The ambient background concentrations provided in Table 3-3 are provided in lieu of ambient pre-construction monitoring. The basis (e.g., data record reviewed, HFH or HSH concentrations, year of observation, etc.) for these values and the reason these are considered representative should be provided. This is especially true as the closest monitor is 42.4 km from the project site. Also, ambient ozone levels should be included.

5. Emission Inventory Other Sources – The following comments are associated with the emission inventory of other sources.
- The 20D procedure only identifies sources that can be considered for elimination from the modeling based on further review. Emissions from sources in close proximity to each other should be summed prior to application of the 20D procedure. The emission sources eliminated using the 20D procedure should be identified.
- PSD minor source baseline dates are receptor dependent. The use of Florence County minor source baseline date is appropriate to identify PSD increment affecting sources if all modeled

receptors are within this county.
- The basis for the emission rates provided for both the NAAQS and PSD inventories should be provided. Comparison of emission rates for common entries in the PSD and NAAQS inventories reveals some differences.
- As expected, emission rates in the PSD emission inventory are equal to, or less than the same entry in the NAAQS inventory. There are occasions in the SO2 inventories where the reverse is true. These conditions need to be explained or corrected.
– The report states that this project establishes the minor source baseline date for Florence County. Except for modifications in major baseline source emissions, a NO2 PSD inventory of other sources is not needed. The need for the NO2 PSD inventory should be explained.
- Most of the negative emission rates in the PSD inventories are associated with emission units that have zero NAAQS emission rates; apparently shut down baseline emission sources. The entries where the NAAQS inventory has positive emission rates and the PSD inventory rate is negative should be explained.

6. Additional Impacts – The following comments are associated with the additional impacts section.
- An analysis of additional growth associated with the project was not provided. The report just states that this analysis is not warranted because no quantifiable air quality impact will occur. The rationale for this statement should be provided.
- Standard 8 toxic air pollutant impacts are not provided because only virgin fuel is burned. Confirmation is needed that pet coke is considered virgin fuel.
- Although the nearest visibility sensitive receptor (i.e., Lake City airport 27 km SW) is outside the SIA for the project, a Level II VISCREEN analysis was performed. Because short-term emission rates should be used in this analysis, the short-term NOx emission rate of 798 lb/hr should be used rather than the 24-hour based 668 lb/hr.

7. Meteorological Data Representativeness – AERMOD adds the surface characteristics of the meteorological site to the representativeness evaluation of the meteorological data for application at the project location. Of specific concern are the albedo, Bowen ratio, and surface roughness within 3 km of the meteorological and project sites. The modeling report refers to Figure B-5 as containing the land use for both the Columbia meteorological site and the Pee Dee project site. This figure only contains land use for the Pee Dee site location at a scale that is too large (spacing of 4 km/square) to determine appropriate land use characteristics.

The report should provide a demonstration of the similarity of the surface characteristics for these two sites as part of the meteorological data representativeness assessment. The basis for, and specific surface characteristics used in the AERMOD modeling should be provided.

8. Modeling Results – The following comments are associated with the reported results from the impact modeling.

- All reported controlling concentrations (e.g., maximum concentrations in Tables 5-1 through 5-8) should be determined from receptor grids of 100-m resolution. This is only applicable to SO2 because this is the only pollutant with a SIA larger than the modeled 100-m resolution grid extending 5 km from the proposed facility.
- The SC DHEC conversion factors for various averaging periods (Table 2-1 of SC Air Quality Modeling Guidelines) were not developed for AERMOD application. Therefore, they may not be appropriate for application to AERMOD concentrations because AERMOD computational methods are very different from that of the SCREEN3 and ISCST models.
- The maximum NO2 concentrations in Table 5-2 significance evaluation and Table 5-12 PSD increment results should be the same because the NO2 PSD minor source baseline date for Florence County is being set by this project. The reason NO2 concentrations in these tables are not the same should be provided.
- The annual PM10 concentration in Table 5-13 PSD increment results should be equal to or larger than the values in Table 5-3 significant evaluation. The reason two of the Table 5-13 annual concentrations are smaller should be provided.
- The 24-hour SO2 concentrations in Table 5-14 increment results should be equal to, or larger than those in Table 5-4. The reason the maximum annual concentration for 1987 in Table 5-14 is smaller should be provided.

Again, please let me know if you have any questions or want to discuss any comment.
Thanks...sjk

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Santee Cooper Meeting re: Santee Cooper Pee Dee PSD Construction Permit
Thursday, May 31, 2007

1) Draft SUSD condition for permit
   a. Attached language
   b. Cliffside preliminary determination
   c. Updated condition 14

2) CO limit
   a. 0.15 lb/mmBTU
   b. Longleaf permit

3) H_2SO_4 limit
   a. 0.005 lb/mmBTU, no higher limit for the first year
   b. Longleaf permit (no additional control)
   c. Cliffside preliminary determination (wet ESP)

4) Class II modeling should be on the way from Trinity
   a. Most recent version of AERMOD
   b. Updated SO_2 modeling
   c. Updated NO_x modeling
   d. PM emissions unchanged

5) Other EPA comments

6) IGCC letter update

Public notice in July

large Q+A meeting late June

CLASS I AREA AIR QUALITY MODELING PROTOCOL
SOUTH CAROLINA PUBLIC SERVICE AUTHORITY
PEE DEE CONSTRUCTION SITE

FLORENCE COUNTY, SOUTH CAROLINA

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April 2007

Trinity Consultants

CLASS I AREA AIR QUALITY MODELING PROTOCOL I

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1. EXECUTIVE SUMMARY

South Carolina Public Service Authority, also known as Santee Cooper, is planning to construct a new coal-fired power plant located near Kingsburg, South Carolina. The plant would consist of combustion boiler technology and ancillary equipment to produce steam for the generation of electricity. Only the emissions from the combustion boiler equipment are expected to have a significant impact on the Class I areas, and thus other sources are excluded from this portion of the modeling analysis.

The scope of the project will require an air quality permit issued under the Prevention of Significant Deterioration (PSD) permitting rules as facility emissions exceed the major source threshold for several PSD pollutants.

Air quality modeling analyses of impacts on federally protected Class I areas are an essential component of PSD review, and are performed to demonstrate compliance with PSD Class I Increment standards and air quality related values (AQRV) thresholds for regional haze and deposition. The CALPUFF modeling system is currently the recommended model for assessment of long-range pollutant transport and chemical transformation. This Class I modeling protocol has been prepared for Fish and Wildlife Service's (FWS)'s review as the Federal Land Manager (FLM) of Cape Romain National Wildlife Refuge (NWR), approximately 100 km to the south of the proposed facility, along South Carolina's coast.

This Class I modeling protocol is also provided to South Carolina Department of Health and Environmental Control (DHEC) for review as part of the PSD application review process.

The modeling methods used in these analyses are consistent with the Interagency Workgroup on Air Quality Modeling (IWAQM) *Phase 2 Summary Report*, the Federal Land Managers' Air Quality Related Values Workgroup (FLAG) *Phase I Report*, the U.S. EPA's *Guideline on Air Quality Models* (*Guideline*), the U.S. EPA's *Regional Haze Regulations and Guidelines for Best Available Retrofit Technology* and communication between Santee Cooper, Trinity Consultants (Trinity), the FLM, and DHEC.[1,2,3,4,5,6].

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[1] U.S. EPA, *IWAQM Phase 2 Summary Report and Recommendations for Modeling Long-Range Transport Impacts*, Research Triangle Park, North Carolina, EPA-454/R-95-006, 1995.

[2] U.S. Forest Service – Air Quality Program, National Park Service – Air Resources Division, U.S. Fish and Wildlife Service – Air Quality Branch, *Phase I Report of the Federal Land Managers' Air Quality Related Values Workgroup (FLAG)*, December 2000.

[3] 40 CFR Part 51, Appendix W (Revised, April 15, 2003).

[4] U.S. EPA, *Regional Haze Regulations and Guidelines for Best Available Retrofit Technology*, June 15, 2005.

[5] Modeling protocol and addendums submitted to FLM on March 17, 2006, April 10, 2006, and May 26, 2006. March 22, 2006 meeting between Santee Cooper, Trinity Consultants, and the FLM.

The remainder of this modeling protocol is organized as follows. Section 2 provides a brief description of the facility and the proposed project. Section 3 describes the procedural and technical guidance for conducting Class I area analyses. Section 4 describes the approach for CALPUFF modeling, including the data resources and technical modeling options used in the CALMET, CALPUFF, and CALPOST analyses.

[6] Letter sent on March 23, 2007 from John Glass (SC DHEC) to Julie Metts (Santee Cooper).

This section describes the overall operations of the Pee Dee facility, and summarizes PSD permitting applicability of the proposed project. Santee Cooper proposes to construct a coal-fired generating facility at the Pee Dee site. The cooling towers and ancillary sources in operation at the facility will not have a significant impact on the Class I areas of concern due to their relatively low emissions and low height of release, and thus are not included in the modeling. With the recent shortages in natural gas supplies, the proposed clean coal-fired power generating station will provide an important source of power that is both reliable and cost-effective and that will have minimal impacts on the environment.

2.1 SITE DESCRIPTION

The new plant will be on 2,700+ acres of land near Kingsburg, SC, approximately 40 km to the southeast of Florence, SC. The Great Pee Dee River borders the northern and eastern edges of the site. There are rural lands to the south and west of the site.

2.2 EMISSIONS

The following pollutant emissions are relevant for Class I modeling: sulfur dioxide (SO_2), oxides of nitrogen (NO_X), particulate matter less than 10 microns in aerodynamic diameter (PM_{10}), and sulfuric acid (H_2SO_4). The emissions from the combustion boiler equipment will be vented through a single stack with two flues. Table 2-1 summarizes the emission rates and stack parameters that will be used in the Class I modeling. Emissions shown are for both boilers.

TABLE 2-1. COAL BOILER EMISSIONS AND STACK PARAMETERS (BOTH UNITS)

Parameter	Value	Units
Stack Height	650	feet
Stack Diameter	25	feet
Exit Velocity	60	feet/s
Exit Temperature	122	°F
SO_2 Emissions	1,368	lb/hr
NO_X Emissions	798	lb/hr
Total PM_{10} (filterable + condensable)	205	lb/hr
Sulfuric Acid Emissions	57	lb/hr

2.2.1 PM SPECIATION

Modeling of visibility impairment due to emissions requires that the components of the exhaust stream be speciated because different size and phases of particulate matter affect visibility to varying extents. The amount by which a mass of a certain species scatters or absorbs light is termed the extinction efficiency or coefficient, and ranges from values of

0.6 m^2/g for coarse particulate matter to 10 m^2/g for elemental carbon for non-hygroscopic particles. Fine particulate matter and organic aerosols scatter light with intermediate efficiencies, and ammonium sulfate and ammonium nitrate (that forms from precursor SO_2 and NO_X emissions in the presence of ambient ammonia) are particularly efficient light scatters in the presence of ambient water vapor.

Speciated emissions of PM associated with coal combustion at the Pee Dee site were estimated based on engineering estimates, Best Available Control Technology (BACT) limits, and AP-42 emissions data. Total PM_{10} (filterable plus condensable) emissions are based on a BACT limit of 0.018 lb/MMBtu. All PM_{10} condensable emissions are conservatively assumed to be sulfate, which has a BACT limit of 0.005 lb/MMBtu. Emissions are further speciated for inclusion in CALPUFF modeling as shown in Table 2-2.

TABLE 2-2. SPECIATED PM EMISSION RATES

Category	CALPUFF Abbreviation	% of PM filterable	% of PM Condensable	Emissions - 2 Units (lb/hr)
PM Coarse	PMC	56.7%	-	84.1
PM Fine	PMF	39.6%	-	58.7
Organic Carbon	OC	-	-	-
Elemental Carbon	EC	3.7%	-	5.5
Ammonium Sulfate	SO_4		100%	57.0

Filterable PM emissions were speciated into $PM_{2.5\text{-}10}$ and $PM_{2.5}$ based on size distribution data in AP-42, Table 1-1.6, *Cumulative Particle Size Distribution and Size-Specific Emission Factors for Dry Bottom Boilers Burning Pulverized Bituminous and Subbituminous Coal.*[7] According to AP-42 data, 56.7% of filterable PM_{10} is greater than 2.5 microns for units with electrostatic precipitators (ESP). All of the $PM_{2.5\text{-}10}$ is classified as PM Coarse (PMC). Of the 43.3% filterable $PM_{2.5}$ emissions, 39.6% were classified as PM Fine (PMF) and 3.7% were allocated to elemental carbon (EC). The value of 3.7% for elemental carbon is based on Table 6 of EPA's January 2002 DRAFT *Catalog of Global Emissions Inventories and Emission Inventory Tools for Black Carbon*.

The size for all speciated PM, except PMC is assumed to be 0.48 μm with a standard deviation of two. The PMC particle size distribution has a mean of 7.5 μm with a standard deviation of two. These values are estimated based on a bimodal size distribution and AP-42 data on the size of coal combustion PM.

[7] U. S. EPA, AP-42, *Compilation of Air Emissions Factors* (5th Edition), Section 1.1 Bituminous and Subbituminous Coal Combustion.

2.2.2 CLASS I INCREMENT INVENTORY

In addition to evaluation of impacts from Santee Cooper, emissions from regional sources will be included in modeling for pollutants that exceed the Class I significance level. For SO_2, a regional emissions inventory was prepared. Unlike Class II regional inventories, there are no specific guidelines for source inclusion for Class I Increment. Based on conversations with the DHEC[8] and past analyses submitted for Cape Romain, a regional inventory was developed based on the following guidelines:

1. Develop a list of all increment consumers and expanders from the eastern-half of South Carolina and any counties in North Carolina within 100 km of the Pee Dee site. A list of included counties is shown in Table 2-3.
2. Include all increment sources less than 100 km from Cape Romain
3. For sources between 100 km and 200 km from Cape Romain, include sources if the facility total increment potential emissions[9] are greater than 100 tpy of any PSD pollutant.
4. For sources greater than 200 km from Cape Romain, include sources if the facility total increment potential emissions are greater than 250 tpy of any PSD pollutant.

TABLE 2-3. COUNTIES REVIEWED FOR SO_2 INCREMENT

Bladen, NC	Charleston, SC	Horry, SC
Columbus, NC	Chesterfield, SC	Jasper, SC
Robeson, NC	Clarendon, SC	Kershaw, SC
Scotland, NC	Colleton, SC	Lee, SC
Aiken, SC	Darlington, SC	Lexington, SC
Allendale, SC	Dillon, SC	Marion, SC
Bamberg, SC	Dorchester, SC	Marlboro, SC
Barnwell, SC	Fairfield, SC	Orangeburg, SC
Beaufort, SC	Florence, SC	Richland, SC
Berkeley, SC	Georgetown, SC	Sumter, SC
Calhoun, SC	Hampton, SC	Willamsburg, SC

Note that emissions from other Santee Cooper sources (Cross and Winyah Generating stations) will be updated to reflect the most recent permit information and may not match DHEC's data. In addition, separate 3-hour and 24-hour runs will be included for Santee Cooper's Cross Generating Station, as the facility has separate 3-hour and 24-hour limits.

[8] Personal communication between Mr. John Glass (DHEC) and Ms. Maria Zufall (Trinity Consultants), February 6, 2006.

[9] Facility total increment emissions are the sum of the absolute values of increment emissions to account for both increment expanders and consumers. Increment emissions are those provided by the state agency.

A table of SO_2 sources that will be included in the inventory is included in Appendix A and a plot of the source locations is provided in Figure B-1.

Two principal air quality impacts are considered for Class I areas: PSD Increments for NO_X, SO_2, and PM_{10}, and air quality related values (AQRV). This section of the protocol describes the procedural requirements for assessing the impacts of Santee Cooper's Pee Dee facility on Cape Romain. Note that the FWS also manages Swanquarter NWR, approximately 320 km northeast of the proposed facility and Wolf Island NWR, approximately 330 km south of the proposed facility. Based on discussions with the FLM, the more distant Class I areas will not be included in the modeling analyses.[10]

The methods described in this modeling protocol are consistent with the Interagency Workgroup on Air Quality Modeling (IWAQM) *Phase 2 Summary Report*, the Federal Land Managers' Air Quality Related Values Workgroup (FLAG) *Phase I Report*, the U.S. EPA's *Guideline on Air Quality Model*s (*Guideline*), the U.S. EPA's *Regional Haze Regulations and Guidelines for Best Available Retrofit Technology* and discussions with the FLM and DHEC.[11,12, 13, 14]

3.1 CLASS I PSD INCREMENT

In general, all PSD permit applications are required to demonstrate through air quality modeling that the emissions increases from the proposed project will not cause or contribute to any violations of allowable increments within affected Class I areas, which are protected to a greater degree (i.e., the allowable increments are lower) than Class II areas. A significant contribution to Class I Increment consumption is defined as a modeled concentration in excess of the significant impact levels summarized in Table 3-1, which were originally developed as part of the 1996 NSR reform rulemaking and have subsequently been adopted as informal modeling significance levels for Class I analyses that are used to inform decision making as to whether a project is likely to cause or contribute to an adverse impact.

[10] March 22, 2006 meeting between Santee Cooper, Trinity Consultants, and the FLM.

[11] U.S. EPA, *IWAQM Phase 2 Summary Report and Recommendations for Modeling Long-Range Transport Impacts*, Research Triangle Park, North Carolina, EPA-454/R-95-006, 1995.

[12] U.S. Forest Service – Air Quality Program, National Park Service – Air Resources Division, U.S. Fish and Wildlife Service – Air Quality Branch, *Phase I Report of the Federal Land Managers' Air Quality Related Values Workgroup (FLAG)*, December 2000.

[13] 40 CFR Part 51, Appendix W (Revised, April 15, 2003).

[14] U.S. EPA, *Regional Haze Regulations and Guidelines for Best Available Retrofit Technology*, June 15, 2005.

TABLE 3-1. CLASS I PSD INCREMENTS AND MODELING SIGNIFICANCE LEVELS

Pollutant	Averaging Period	Class I Increment ($\mu g/m^3$)	Significance Level ($\mu g/m^3$)
PM_{10}	24-hour	8.0	0.32
	Annual	4.0	0.16
SO_2	3-hour	25.0	1.0
	24-hour	5.0	0.2
	Annual	2.0	0.1
NO_2	Annual	2.5	0.1

Because the Pee Dee facility will cause significant emission increases of NO_X, SO_2 and PM_{10}, the Class I air quality analysis assesses Class I PSD Increment for each of the species. If the significance level for any of these pollutants is exceeded, a regional inventory is developed and the impacts of the Pee Dee facility and the regional inventory are compared against the Class I increment. As discussed in Section 2.2.2, an inventory analysis will be conducted for SO_2.

The PM_{10} increment consists of PMC, PMF, secondary organic aerosols (SOA), and EC as modeled in CALPUFF.

3.2 CLASS I AQRV ANALYSES

With the exception of visibility, the Clean Air Act and the PSD regulations do not define AQRV, do not provide procedures for defining AQRV, and do not provide criteria to determine critical pollutant loadings at which an adverse impact on AQRV would occur. The FLM AQRV Workgroup (FLAG) December 2000 Phase I report defines the following:[15]

> *Air Quality Related Value* - A resource, as identified by the FLM for one or more Federal areas, that may be adversely impacted by a change in air quality. The resource may include visibility or a specific scenic, cultural, physical, biological, ecological, or recreational resource identified by the FLM for a particular area.
>
> *Adverse Impact on Air Quality Related Values* - A deleterious effect on any AQRV defined by the FLM, resulting from the emissions of a proposed sources or modification, that interferes with the management, protection, preservation, or enjoyment of the AQRV.

AQRV indicators typically identified by FLM include nitrogen deposition, sulfur deposition, and visibility degradation. The following sections discuss the AQRV addressed for this project.

[15] U.S. Forest Service – Air Quality Program, National Park Service – Air Resources Division, U.S. Fish and Wildlife Service – Air Quality Branch, *Phase I Report of the Federal Land Managers' Air Quality Related Values Workgroup (FLAG)*, December 2000.

3.2.1 DEPOSITION

In the deposition analysis, the Pee Dee facility's contribution to the deposition of chemical species in the Class I area will be evaluated against the deposition assessment threshold (DAT) values for sulfate and nitrate set by the FLM. The DAT represents "the additional amount of N or S deposition within a Class I area, below which estimated impacts from a proposed new or modified source are considered insignificant."[16] The threshold is not necessarily an adverse impact threshold and coastal ecosystems have evolved under naturally higher sulfur deposition rates.[17] FLM guidance for assessment of deposition impacts suggests that an appropriate sulfur and nitrogen DAT is 0.01 kg/ha/yr (each) for Class I areas in the Eastern United States.[18]

Gas-phase dry deposition will be modeled for SO_2, NO_X, and HNO_3. Particulate-phase dry deposition will be modeled for SO_4, NO_3, and PM_{10}. Wet deposition will be modeled for SO_2, SO_4, HNO_3, and NO_3. The sum of wet and dry deposition fluxes for SO_2 and SO_4 represents the total sulfur deposition as shown in Equation 1.

$$\text{Sulfur Deposition (kg/ha/yr)} = \left(\text{flux}\,[SO_2] + \text{flux}\,[(NH_4)_2SO_4]\right)_{\text{wet}} + \left(\text{flux}[SO_2] + \text{flux}[(NH_4)_2SO_4]\right)_{\text{dry}}$$

Equation 1

The sum of wet and dry deposition fluxes for NO_X, NO_3, HNO_3, and ammonium ion (NH_4) from ammonium nitrate and sulfate represent the total nitrogen deposition, as shown in Equation 2.

$$\text{Nitrogen Deposition (kg/ha/yr)} = \left(\text{flux}[NH_4NO_3] + \text{flux}[HNO_3] + \text{flux}[(NH_4)_2SO_4]\right)_{\text{wet}} + \left(\text{flux}[NOx] + \text{flux}[NH_4NO_3] + \text{flux}[HNO_3] + \text{flux}[(NH_4)_2SO_4]\right)_{\text{dry}}$$

Equation 2

The contribution of the proposed project to the deposition of nitrogen and sulfur species in each Class I area will be estimated and assessed against the DAT in the modeling report.

3.2.2 VISIBILITY

Visibility can be affected by plume impairment (heterogeneous) or regional haze (homogeneous). Plume impairment results when there is a contrast or color difference between the plume and a viewed background (the sky or a terrain feature). Plume impairment is generally only of concern when the Class I area is near the proposed source

[16] U.S. National Park Service - Air Resources Division and U.S. Fish and Wildlife Service - Air Quality Branch, *Guidance on Nitrogen and Sulfur Deposition Analysis Thresholds*, May 2002.

[17] *Ibid*.

[18] *Ibid*.

(i.e., less than 50 km). Since the distance between the Pee Dee facility and the Class I area evaluated is greater than 50 km, only regional haze will be considered in this analysis.

Regional haze occurs at distances where the plume has become evenly dispersed into the atmosphere such that there is no definable plume. The primary causes of regional haze are sulfates (SO_4) and nitrates (NO_3) (primarily as ammonium salts), which are formed from emissions of SO_2 and NO_X through chemical reactions in the atmosphere. These reactions take time, hence distance. Near a source little NO_X or SO_2 will have formed nitrate or sulfate, whereas far from a source nearly all SO_2 will have formed sulfate and most NO_X will have formed nitrate. Particulate emissions also contribute to regional haze but to a lesser extent since sulfates and nitrates are hygroscopic species that increasingly reduce visibility with increased relative humidity.

Regional haze is measured using the light extinction coefficient (b_{ext}). To determine a change in regional haze, the percentage change of the light extinction coefficient (Δb_{ext}) will be evaluated as shown in the following Equation 3:

$$\Delta b_{ext} = \frac{b_{ext,project}}{b_{ext,background}}$$

Equation 3

The background extinction coefficient $b_{ext,\ background}$ is affected by various chemical species and the Rayleigh scattering phenomenon and can be calculated as shown in Equation 4:[19]

$$b_{ext,background}\,(km^{-1}) = b_{SO_4} + b_{NO_3} + b_{OC} + b_{soil} + b_{coarse} + b_{ap} + b_{ray}$$

Equation 4

where,

$$b_{SO_4} = 0.003\left[(\mathrm{NH}_4)_2\mathrm{SO}_4\right] f(RH)$$
$$b_{NO_3} = 0.003\left[\mathrm{NH}_4\mathrm{NO}_3\right] f(RH)$$
$$b_{OC} = 0.004\left[\mathrm{OC}\right]$$
$$b_{Soil} = 0.001\left[\mathrm{Soil}\right]$$
$$b_{Coarse} = 0.0006\left[\text{Coarse Mass}\right]$$
$$b_{ap} = 0.01[\text{Elemental Carbon}]$$
$$\mathrm{b}_{\mathrm{Ray}} = \text{Rayleigh Scattering}$$
$$\mathrm{f(RH)} = \text{relative humidity adjustment factor}$$
$$[\quad] = \text{Concentration in } \mu g/m^3$$

Values for the parameters listed above specific to the natural background conditions at the Class I area considered in this analysis are provided on an annual average basis in the

[19] U.S. Forest Service – Air Quality Program, National Park Service – Air Resources Division, U.S. Fish and Wildlife Service – Air Quality Branch, *Phase I Report of the Federal Land Managers' Air Quality Related Values Workgroup (FLAG)*, December 2000.

U.S. EPA's *Guidance for Estimating Natural Visibility Conditions Under the Regional Haze Rule*.[20] The values are shown in Table 3-2.

TABLE 3-2. ANNUAL AVERAGE BACKGROUND VALUES

Species	Average Concentration ($\mu g/m^3$)
Ammonium Sulfate	0.23
Ammonium Nitrate	0.10
Organic Carbon Mass	1.40
Elemental Carbon	0.02
Soil	0.50
Coarse Mass	3.0

The extinction coefficient due to emissions increases from the proposed project $b_{ext,project}$ are also be calculated. Pollutants that have the potential to affect visibility (SO_2, NO_X, and particulate species) will be emitted from the proposed project. The extinction due to the project is calculated as shown in Equation 5.

$$b_{ext,project}(km^{-1}) = b_{SO_4} + b_{NO_3} + b_{PMF} + b_{PMC} + b_{SOA} + b_{EC}$$

Equation 5

where,

$$b_{SO_4} = 0.003\left[(NH_4)_2SO_4\right] f(RH)$$
$$b_{NO_3} = 0.003\left[NH_4NO_3\right] f(RH)$$
$$b_{PMC} = 0.0006[PMC]$$
$$b_{PMF} = 0.001[PMF]$$
$$b_{soa} = 0.004[SOA]$$
$$b_{EC} = 0.01[EC]$$
$$f(RH) = \text{relative humidity adjustment factor}$$
$$[\quad] = \text{Concentration in } \mu g/m^3$$

Particulate species and precursors that affect visibility are emitted in various phases and include PMC, PMF, SOA, and EC. In this analysis, an upper bound will be placed on the relative humidity function such that no *f*(RH) factors are applied greater than *f*(95%) to the extinction caused by hygroscopic sulfate and nitrate species.

The Δb_{ext} value attributable to a single facility that is generally acceptable to the FLM is 5% on a 24-hour average basis. Values above 10% are interpreted to indicate that a cumulative visibility analysis should be performed. However, the "FLM is required to

[20] U.S. EPA, *Guidance for Estimating Natural Visibility Conditions Under the Regional Haze Rule*, Table 2-1, Attachment A, September 2003, EPA-454/B-03-005.

make a determination on a "…case-by-case basis taking into account the geographic extent, intensity, duration, frequency and time of visibility impairments."[21]

There are a number of methods for the FLM to review the intensity, duration, frequency and time of visibility impairments. These alternative modeling options are discussed in detail in the following sections. Per discussions with the FLM, results from each of the different scenarios will be presented in the modeling report.[22]

The peak 24-hour average visibility impairment as predicted by the air quality model is typically used to attribute visibility affects to a single source. However, the recently promulgated Regional Haze Regulations and *Guidelines for Best Available Retrofit Technology* establish a different metric for assessing whether a single facility causes or contributes to visibility impairment. This guidance establishes a 0.5 deciview (dv) (roughly equivalent to 5% extinction change) threshold for contribution and 1.0 dv (approximately 10% extinction change) threshold for causation of visibility impairment. These thresholds are essentially equivalent to the FLAG guidance, except that they are to be applied to the 98th percentile model result for an analysis that considers multiple years of meteorological data. In other words, application of the 98th percentile standard formalizes the intensity, duration, and frequency aspects of modeled visibility impairment events by standardizing discretion left to the FLM on a case-by-case basis to exclude visibility impairment events that could be due to meteorological conditions or other naturally occurring phenomena that are not attributable to the emissions source. Visibility modeling results will be presented at both peak and 98th percentile levels to demonstrate two interpretations of the model results.

As further described in Section 4 of this Class I modeling protocol, this analysis will utilize the CALPOST processor to assess impacts from the proposed project on regional haze. The IWAQM recommended "Method 2," which uses hourly relative humidity adjustment applied to background and modeled sulfate and nitrate with the relative humidity factor capped at 95%, will be used to compute visibility impairment in terms of Δb_{ext} from modeled pollutant concentrations. This postprocessing option uses observed relative humidity values and pollutant concentrations at each receptor to compute the percent change in visibility due to the facility's emissions compared against the natural background visibility under the prevailing atmospheric conditions. Method 2 is considered the default approach under FLAG.

An alternative approach, "Method 6," computes Δb_{ext} using a *monthly average* relative humidity adjustment particular to each Class I area applied to background and modeled sulfate and nitrate. Because a monthly average is used, no cap on f(RH) is necessary since the function is not used in Method 6 and the results tend to be smoothed out since peak short-term humidity events are not considered. Method 6 is not typically considered a default approach for PSD AQRV analyses, but is used to assess visibility impairment under

[21] (40 CFR §51.301 (a)).

[22] March 22, 2006 meeting between Santee Cooper, Trinity Consultants, and the FLM.

the U.S. EPA's *Guidelines for Best Available Retrofit Technology*, in particular in the VISTAS regional planning organization that encompasses the Southeastern U.S.[23] The monthly f(RH) values are shown in Table 3-3.

TABLE 3-3. MONTHLY AVERAGE *f*(RH) FOR CAPE ROMAIN*

January	February	March	April	May	June	July	August	September	October	November	December
3.3	3.0	2.9	2.8	3.2	3.7	3.6	4.1	4.0	3.7	3.4	3.2

*As tabulated in Table A-3 of U.S. EPA's *Guidance for Estimating Natural Visibility Conditions under the Regional Haze Rule* (2003).

Visibility modeling results for the Pee Dee facility will be presented using Method 2 and Method 6 to inform the FLM and South Carolina DHEC of each interpretation of model results and to illustrate the frequency of visibility impairment events that are caused by naturally occurring weather conditions.

In addition, VISTAS has recently provided a post-processing tool to allow existing CALPOST outputs to be used in an updated IMPROVE equation.[24] The new IMPROVE equation takes into account the effects of both sea-salt and Rayleigh scattering on visibility impairment.

Visibility modeling results for the Pee Dee facility will also be presented using the existing IMPROVE equation and the new IMPROVE post-processing tool. Note that the new IMPROVE equation tool will be utilized with the currently listed default values for sea salt at Cape Romain. However, DHEC and VISTAS are in the process of reviewing revised sea-salt data. The results may also be presented with the updated sea salt values.[25]

[23] VISTAS, "Protocol for the Application of the CALPUFF Model for Analyses of Best Available Retrofit Technology (BART)," December 22, 2005.

[24] Ivar Tombach, "A Postprocessor for Recalculating CALPOST Visibility Outputs with the New IMPROVE Algorithm," October 2006.

[25] April 3, 2007 BART Conference call with John Glass (SC DHEC).

4. CLASS I AREA MODELING METHODS

The preferred model for analyzing long-range pollutant transport (i.e., distances greater than 50 km) is the CALPUFF modeling system. The EPA-approved version (Version 5.711a of CALPUFF, 5.53a of CALMET, and 5.51 of CALPOST) of the CALPUFF model will be used to determine the possible impacts of the proposed Pee Dee facility on Class I PSD Increment and AQRV at Cape Romain. The VISTAS version (Version 5.756 of CALPUFF, 5.726 of CALMET, and 5.6393 of CALPOST) of the CALPUFF modeling system is currently being used to address the Regional Haze Rule (RHR) for the VISTAS region. As the FLM are currently reviewing a number of VISTAS regional haze analyses, this modeling demonstration will utilize much of the same data as used in the VISTAS regional haze analyses. The US EPA has recently undertaken evaluation studies that have shown discrepancies between the EPA-approved and VISTAS versions of the CALPUFF model. The CALPUFF development team is currently updating documentation that illustrates the model changes/enhancements that were incorporated into the VISTAS version. The US EPA anticipates approval of the VISTAS version as the regulatory version of CALPUFF once that documentation has been received. Since the timeline for this permit application is shorter than the model review process, the current EPA version will be utilized in this analysis.

CALPUFF is a multi-layer, multi-species, non-steady-state Lagrangian puff model, which can simulate the effects of time- and space-varying meteorological conditions on pollutant transport, transformation, and removal. For this refined analysis, meteorological fields generated by CALMET will be used as inputs to the CALPUFF model to ensure that the effects of terrain and spatially varying surface characteristics on meteorology are considered.

In addition to meteorological data, the CALPUFF model uses several other input files to specify source and receptor parameters. The selection and control of CALPUFF options are determined by user-specific inputs contained in the control file. This file contains all of the necessary information to define a model run (e.g., starting date, run length, grid specifications, technical options, output options). The air quality modeling will be performed using CALPUFF default options unless otherwise noted, as specified in the federal *Guideline* and IWAQM documents. The following sections describe the modeling domain, meteorological data, background concentrations, and model implementation to be used for the analysis of the new Pee Dee Facility.

4.1 MODELING DOMAINS

The meteorological CALMET and computational CALPUFF domains are illustrated in Figure B-2. For the purposes of this analysis, the CALMET and CALPUFF domains will be identical for each analysis and are singularly referred to herein as the "domain." The size of the domain will be 250 km by 352 km, and was selected to encompass both the Pee Dee Facility and the Cape Romain area, to extend at least 50 km beyond Cape Romain and the facility in all directions, and to incorporate all regional inventory sources. The size of the domain will also allow for the possible recirculation of puffs beyond the facility and areas being evaluated.

The horizontal domain is comprised of grid cells, each containing a central grid point at which meteorological and computational parameters are calculated at each time step. For this analysis, grid spacing intervals of 2 km will be used to resolve terrain features within the domain, which is generally flat. Given this interval, the domain will consist of 125 by 176 grid cells. Table 4-1 summarizes the vertical grid structure selected for both analyses. The cell face height of each cell indicates its vertical extent. The vertical domain will be composed of terrain-following grid cells, the number and size of which are chosen so as to constrain the boundary layer in which dispersion and chemical transformations take place. The highest cell face will be 4,000 meters to constrain the default maximum mixing height of 3,000 meters. Ambient impacts are predicted at receptors specified by the FLM to represent Cape Romain.[26]

TABLE 4-1. VERTICAL GRID STRUCTURE

Vertical Grid Cell	Cell Face Height (meters)
1	20
2	40
3	80
4	160
5	320
6	640
7	1,200
8	2,000
9	3,000
10	4,000

Note that the coordinates used in this modeling simulation will be Lambert Conformal Coordinates based on the design of the VISTAS RHR modeling.[27] These coordinates have an origin of 40°N and 97°W with standard parallels of 33°N and 45°N.

4.2 CALMET METEOROLOGICAL PROCESSING

CALMET is the meteorological preprocessor that compiles meteorological data from raw observations of surface and upper air conditions, precipitation measurements, mesoscale model output, and geophysical parameters into a single hourly, gridded data set for input to CALPUFF. The federal *Guideline* for CALPUFF processing provides the following recommendations for the meteorological data period analyzed at Section 9.3.1.2:

> *For LRT situations (subsection 7.2.3) … if only NWS or comparable standard meteorological observations are employed, five years of meteorological data (within and near the modeling domain) should be used. Consecutive years from the most recent, readily available 5-year period are preferred. Less than five, but at least*

[26] http://www2.nature.nps.gov/air/maps/Receptors/index.htm

[27] VISTAS, *Protocol for the Application of the CALPUFF Model for Analyses of Best Available Retrofit Technology (BART)*, December 22, 2005, revised August 31, 2006.

three, years of meteorological data (need not be consecutive) may be used if mesoscale meteorological fields are available, as discussed in paragraph 9.3(c). These mesoscale meteorological fields should be used in conjunction with available standard NWS or comparable meteorological observations within and near the modeling domain.

The FLM frequently prefer the application of mesoscale meteorological (MM) data due to its high resolution, three-dimensional representation of meteorological conditions. Recently, three years of MM data have been developed as part of the RHR modeling: 2001 MM5 data (12 km resolution), 2002 MM5 data (12 km resolution), and 2003 MM5 data (36 km resolution). These data are quality assured, and generally accepted for use in regulatory modeling applications.

4.2.1 GEOPHYSICAL DATA

CALMET requires geophysical data about the domain to characterize the terrain and land use parameters that potentially affect dispersion. Terrain features affect flows and create turbulence in the atmosphere and are potentially subjected to higher concentrations of elevated puffs. Different land uses exhibit variable characteristics such as surface roughness, albedo, Bowen ratio, and leaf-area index that also affect turbulence and dispersion. Terrain and land use and cover data were obtained from the USGS in 1-degree (1:250,000 scale or approximately 90-meter resolution) digital formats. Data preprocessors were used to format and assimilate these data into a single geophysical data file for processing by CALMET. Figures B-3 and B-4 depict the terrain and land use and cover in the modeling domains as represented in CALMET, respectively.

4.2.2 SURFACE METEOROLOGICAL DATA

The use of multiple stations for meteorological observations in CALMET/CALPUFF provides a substantial enhancement over the steady-state treatment of observations from a single meteorological station. Parameters affecting turbulent dispersion that are observed hourly at surface stations include wind speed and direction, temperature, cloud cover and ceiling, relative humidity, and precipitation type. Surface data stations used will be the same as those developed as part of the RHR VISTAS modeling developed by the VISTAS contractor. Surface stations are shown in Figure B-5. Note that the use of the VISTAS data set includes a large number of stations based on the VISTAS domain. As the impact of each station is weighted by distance and those stations beyond a certain distance are not included, these more distant stations will not impact the analysis.

4.2.3 UPPER AIR DATA

Observations of meteorological conditions in the upper atmosphere provide a profile of turbulence from the surface through the depth of the boundary layer in which dispersion occurs. Upper air data are collected by balloons launched simultaneously across the observation network at 0000 Greenwich Mean Time (GMT) (7 o'clock PM in South Carolina) and 1200 GMT (7 o'clock AM in South Carolina). Sensors observe pressure, wind speed and direction, and temperature (among other parameters) as the balloon rises through the atmosphere. The upper air observation network is less dense than surface

observation points since upper air conditions vary less and are generally not as affected by local effects (e.g., terrain or water bodies). As with the surface data, upper air data will be the same as is incorporated in the VISTAS RHR analyses completed by the VISTAS contractor. Figure B-6 shows the locations of the upper air stations.

4.2.4 PRECIPITATION DATA

Trinity will consider the effects of chemical transformations and deposition processes on ambient pollutant concentrations in this analysis. Therefore, it will be necessary to include observations of precipitation in the CALMET analysis. Precipitation data will be collected from selected surface meteorological data stations included in the analysis, plus Cooperative Observation Network (COOP) stations nearer to or within the domain. Precipitation data will be the same as is incorporated in the VISTAS RHR analyses completed by the VISTAS contractor. Figure B-7 shows the locations of the precipitation stations.

4.2.5 OVERWATER DATA

Because parts of the modeling domain encompass the open waters of the Atlantic Ocean and Cape Romain located along the Atlantic Coast, Trinity will include meteorological data from buoys to utilize overwater meteorological processing algorithms in CALMET.

The critical differences in behavior of the inland and marine boundary layers, and atmospheric dispersion phenomena occurring within these distinct regimes, is well documented and recognized to play a vital role in the dispersion of pollutants originating in, or destined to affect, coastal areas. Key phenomena occurring in coastal environments that affect pollutant dispersion include land/sea-breezes that cause recirculation of pollutant mass, temperature moderation that results in sharp gradients and mixing height discontinuities at the land-sea interface, and thermal internal boundary layers that could cause severe fumigation under certain conditions. The CALMET processor is equipped to assimilate overwater data obtained from coastal, near-shore, and offshore observation platforms. CALMET uses a profile method to simulate boundary layer effects by computing the friction velocity, Monin-Obukhov length, surface roughness, and mixing height over the water surface. The details of the formulation of marine dispersion algorithms are provided in the documentation accompanying the CALPUFF modeling system.

To perform its simulation of the coastal environment, CALMET requires hourly observations of air temperature, air-sea temperature difference, wind speed and direction, relative humidity, overwater mixing height, and the overwater temperature gradients above and below the overwater mixing height. For practical applications of overwater boundary layer computations, these data can be obtained in part from the National Data Buoy Center (NBDC). The NBDC maintains an inventory of standard meteorological data observed by ships, buoys, and C-MAN stations in coastal, near-shore, and offshore locations.

NDBC's data sets provide direct wind and temperature measurements, and relative humidity can be inferred from pressure and dewpoint observations. The mixing height and

temperature gradients and default values must be applied by CALMET when simulating the coastal atmosphere. Buoy data will be the same is incorporated in the VISTAS RHR analyses completed by the VISTAS contractor. Figure B-8 shows the locations of the over-water stations.

4.2.6 MESOSCALE MODEL OUTPUT

Output from mesoscale meteorological (MM) forecast models is an ideal input for air quality models because parameters that characterize the state of turbulence in the atmosphere are diagnosed on a high resolution, three-dimensional grid. For this analysis, output from mesoscale models will be used to provide the "initial guess" wind field for CALMET processing, using 2001 MM5 data (12 km resolution), 2002 MM5 data (12 km resolution), and 2003 MM5 data (36 km resolution). Note that the MM data developed for VISTAS do not include information for the first day of 2004 which is required to process the last day of 2003. Therefore, only 364 days will be modeled for 2003. Figure B-9 shows the extraction domains of meteorological data to be used in the primary analysis.

Using this approach, the wind field at grid points within the horizontal and vertical CALMET domain will be initially interpolated from the MM grid. Observations of winds from surface and upper air stations (which may in fact be quite distant from a particular CALMET grid point) will subsequently be interpolated using an inverse-distance scheme to define the meteorological fields within the domain.

4.2.7 CALMET PROCESSING CONTROL

CALMET assimilates all of the surface, upper air, precipitation, geophysical, and mesoscale data described in the previous sections into a single hourly, gridded data file for use by CALPUFF. This file contains winds, temperature, micrometeorological variables, and turbulence parameters necessary for CALPUFF to make dispersion, chemical transformation, and deposition computations at each grid cell and time step. A control file contains all the inputs to run the CALMET processor. For this analysis, default values will be used with the following exceptions, for which there is no default parameter or case-by-case analysis is warranted.

As previously discussed, MM data are used as the initial guess wind field and subsequently adjusted using NWS observations of surface and upper air winds. Default options for kinematic effects, divergence minimization, Froude number adjustment, and computation of slope flows will be enabled to allow for local adjustment of wind fields introduced by MM data.

The choice of the radius of influence of the surface observations (RMAX1), upper air observations (RMAX2), and offshore buoy observations (RMAX3) is left to the discretion of the user since there are no accepted default values provided, for example, by the Interagency Workgroup on Air Quality Modeling (IWAQM) *Phase 2 Summary Report and*

Recommendations for Modeling Long Range Transport Impacts.[28] Appendix A of the IWAQM report provides recommended default CALMET settings, but there is no default for RMAX1, RMAX2, and RMAX3. Santee Cooper is not aware of other guidance that would define what is normally used for these parameters for analyses conducted in the Southeastern U.S. and in particular the regions of South Carolina, North Carolina, and Georgia that encompass these analyses. The model developer has posted general technical guidance addressing typical considerations for these model settings.[29]

The settings of RMAX1, RMAX2, and RMAX3 cause the CALMET model to use observed wind measurements in the Step 2 wind field computation wherein the observations are blended with the first-guess windfield generated from MM5 wind data to represent local effects (e.g., terrain) that may not be resolved in the lower resolution (e.g., 12 km [2001 and 2003] or 36 km [2003]) MM data. Note that in conjunction with the RMAX settings, LVARY will be set to false so that the weight of observations would be limited within these radii and CALMET would not artificially use observed values for portions of the grid outside of the observation radius.

The selection of RMAX1 = 40 km, RMAX2 = 40 km, and RMAX3 = 100 km is justified by the relative scarcity of uniform surface, upper air, and buoy observations within the large modeling domain. Therefore, the use of supplementary observation stations beyond the modeling domain and an adequately large radius of influence will be necessary to cover the majority of the domain.

Trinity also notes that additional parameters, R1 and R2, control the relative weighting of observed and first-guess MM5 data. R1 (surface) and R2 (upper air) represent the distance at which the observation and MM data are equally weighted, and are the more relevant parameters for assessing the relative weight of surface and upper air observations compared to the MM5 wind field. The values of R1 and R2 will each be set to the relatively small value of 5 km to balance the resolution of MM5 data (12 km or 36 km) and the lower density of NWS observations.

4.3 CALPUFF MODEL PROCESSING

Using the data provided by CALMET, CALPUFF simulates the dispersion, deposition, and chemical transformation of discrete puffs of mass from emission sources. Each puff contains emissions of NO_X, SO_2, and PM_{10} and is advected throughout the domain while deposition and chemical transformation processes take place. CALPUFF is a Lagrangian puff model, the principle advantages of which are that pollutant plumes can evolve dynamically and chemically over time and can respond to complex winds caused by terrain effects, stagnation, or recirculation.

[28] U.S. EPA Report EPA-454/R-98-019, December 1998.

[29] http://src.com/calpuff/FAQ-answers.htm#1.1.8

Emissions data for each modeled emission source will be entered into CALPUFF as previously described in Table 2-1 of this protocol. Due to the distance from the source to the Class I areas, building downwash will not be enabled.

This analysis will be performed with the deposition and chemical transformation algorithms enabled. A full resistance model is provided in CALPUFF for the computation of dry deposition rates of gases and particulate matter as a function of geophysical parameters, meteorological conditions, and pollutant species. An empirical scavenging coefficient approach using default options will be enabled in CALPUFF to compute the depletion and wet deposition fluxes due to precipitation scavenging. The CALPUFF model is capable of simulating linear chemical transformation effects by using pseudo-first-order chemical reaction mechanisms for the conversions of SO_2 to SO_4 and NO_X, which consists of nitrogen oxide (NO) and nitrogen dioxide (NO_2), to nitrate (NO_3) and nitric acid (HNO_3). In this study, chemical transformations involving five species (SO_2, SO_4, NO_X, HNO_3, and NO_3) will be modeled using the MESOPUFF II chemical transformation scheme, per IWAQM guidance. There are two user-selected input parameters that affect the MESOPUFF II chemical transformation, ammonia concentrations and ozone concentrations. The selection of each parameter is discussed separately.

4.3.1 OZONE

Ambient ozone concentrations can be input to the model as a background level or using hourly, spatially varying observations. For this analysis, monitored hourly ozone data from each data year from ozone monitors within and near the domain will be included. Operational monitors on the CASTNET and AIRS reporting networks will be reviewed as part of the VISTAS RHR modeling and a subset of these monitors was selected for this analysis. A plot of stations is included in Figure B-10.

4.3.2 AMMONIA

IWAQM Phase 2 recommends the use of spatially constant background ammonia concentrations to participate in the MESOPUFF-II chemical transformation mechanism.[30] In the absence of an extensive monitoring network for ammonia and due to the limitation of CALPUFF to simulate only a single, domain-average background ammonia level for each month of analysis, a single value will be used. The land use analysis presented in Figure B-4 illustrates that the majority of the modeling domain is forested, water, or agricultural area. The IWAQM guidance recommends the ammonia value be set between 0.5 ppb for forested areas and 10 ppb for grasslands. The inland portions of the modeling domain are predominantly forested and the remainder of the domain over the Atlantic Ocean, therefore the ammonia background level will be set at 0.5 ppb for this analysis.

[30] U.S. EPA, *IWAQM Phase 2 Summary Report and Recommendations for Modeling Long-Range Transport Impacts*, Research Triangle Park, North Carolina, EPA-454/R-95-006, 1995 at 14.

4.3.3 CALPUFF PROCESSING CONTROL

CALPUFF modeling will be conducted generally using the recommended regulatory default options specified in Appendix B of the IWAQM guidance. The integrated puff representation will be used and puff splitting will be conservatively disabled.

4.4 VISTAS DATA MODIFICATIONS

Since the VISTAS meteorological and input file templates were created for use in the VISTAS versions of CALMET and CALPUFF, certain modifications will be required in order to run the data in the EPA-approved versions of the models. These changes are discussed in the sections below.

4.4.1 UPDATES TO FILE HEADERS

The headers of each of the following files will be updated to reflect the format of the EPA version files:

- Geophysical Data
- Surface Meteorological Data
- Precipitation Data
- Overwater Data
- Mesoscale Model Data
- Ozone Data

4.4.2 SURFACE METEOROLOGICAL DATA

In addition to file header updates, the surface station ID numbers will be truncated to five digits, as that is the maximum number allowed in the EPA version.

4.4.3 OVERWATER DATA

In addition to the standard wind and air/sea temperature information, the VISTAS version of the overwater data files contain anemometer height, wave height, wave period, and the depth of the water temperature sensor. These additional parameters, which are not used in the EPA-approved version, will be removed prior to processing the data.

4.4.4 MESOSCALE MODEL OUTPUT

Each MM5 output file contains between 2.5 and 4 days of data. The EPA version of CALMET only allows a single MM5 data file to be used per run, and as such, the user would be required to create close to 100 CALMET input files in order to generate a single year of data. The VISTAS files will be appended to create monthly datasets which will allow for more efficient processing in the CALMET model.

4.4.5 CALMET PROCESSING CONTROL

There is a bug in EPA-approved version of CALMET which results in an incorrect air density array being used in the calculation of the daytime convective and mechanical mixing heights. In the CALMET analysis, this bug results in an error being generated and the run being terminated. Upon researching the code, it has been determined that the problematic subroutine (called "mixht") in the current EPA-approved version defines a variable as 1-D array (referring to the index of surface station) while it should be defined as a 2-D array (referring to the grid point index). This bug was corrected and the code recompiled in order to facilitate the runs. The bug was communicated to EPA for confirmation and approval of the revision.[31]

4.4.6 CALPUFF MODEL PROCESSING

The EPA-approved version of CALPUFF only allows for a single meteorological input file (CALMET.dat.) The CALPUFF model will be recompiled to allow for multiple CALMET files (i.e. twelve monthly files) in order to more efficiently complete the model processing.

4.4.7 OZONE

The date record for each observation in the VISTAS data includes both a starting and ending date/time. The ending date/time will have to be removed as the EPA-version assumes hourly data beginning at the starting time in each record of the date file. The extraneous date records prevent the subsequent ozone data from being read properly by CALPUFF.

4.5 CALPOST POSTPROCESSING ANALYSIS

The CALPOST postprocessor will be used to compute the ambient concentrations of SO_2, PM_{10}, and NO_2 at Class I areas for assessment against the PSD Class I Increment modeling significance level, the total deposition of sulfur and nitrogen within each Class I area for assessment against the DAT, and the 24-hour average visibility impairment. Section 3 generally described the technical approach for computing these values from the modeled concentrations of pollutant emissions.

Specifically within CALPOST for deposition calculations, POSTUTIL will be used to combine the appropriate wet and dry fluxes of nitrogen- and sulfur-bearing species deposited as particles and gases. POSTUTIL will also be used to combine the speciated PM (PMC, PMF, SOA, EC) to evaluate PM_{10} increment. CALSUM will be used to combine increment consumers and expanders for regional inventory Class I increment modeling.

Visibility change will be computed using each of Method 2 and Method 6 and results will be reported for the peak and 98th percentile 24-hour average visibility change for each of the three years of meteorological data modeled. Results will also be presented using the new IMPROVE equation, which incorporates background sea salt and the Cape Romain-specific Rayleigh scattering value. The

[31] Email communication on February 19, 2007 from Weiping Dai (Trinity) to Dennis Atkinson (USEPA).

ammonia limiting method (ALM) will be applied to adjust predicted concentrations at the final endpoint.

APPENDIX A

CLASS I INVENTORY SOURCE LIST

Table A-1. Regional Inventory Sources

County	ID	Company Name	Stack Details	SO_2 Emissions (lb/hr)	UTM East (m)	UTM North (m)	Height (ft)	Temp °F	Modeled Velocity (ft/s)	Diameter (ft)
Beaufort	BEA01	US Marines-MCRD Parris Island	CPP4 Boiler 4	-3.66E+00	530,943	3,579,198	65.00	424.00	39.37	3.15
Beaufort	BEA02	US Marines-MCRD Parris Island	WPP5 Boiler 5	-3.79E+01	527,863	3,576,948	35.10	424.00	38.71	1.48
Beaufort	BEA03	US Marines-MCRD Parris Island	WPP6 Boiler 6	5.93E+01	527,866	3,576,951	35.10	424.00	25.59	2.30
Beaufort	BEA04	US Marines-MCRD Parris Island	WPP7 Boiler 7	5.93E+01	527,871	3,576,956	35.10	433.00	25.59	2.30
Beaufort	BEA05	US Marines Corps Air Station	FC1/2 - boilers 1&2	8.92E-02	526,364	3,591,621	73.00	269.00	0.03	4.00
Beaufort	BEA06	US Marines Corps Air Station	Microturbines	8.25E-01	526,355	3,591,605	6.90	170.00	51.18	0.82
Beaufort	BEA07	US Marines Corps Air Station	FC3 - boiler 3	1.71E+00	528,259	3,592,289	25.00	300.00	0.03	1.05
Beaufort	BEA08	US Marines Corps Air Station	TS5 - T10 Test Cell Stack 1	4.79E+00	525,165	3,593,059	40.00	203.00	15.10	13.78
Beaufort	BEA09	US Marines Corps Air Station	TS5 - T10 Test Cell Stack 2	4.79E+00	525,165	3,593,059	40.00	687.00	98.10	13.78
Beaufort	BEA10	Santee Cooper - Hilton Head	Unit 3	3.54E+02	528,328	3,563,489	32.00	990.00	120.00	15.00
Beaufort	BEA11	Ulmer Brothers Inc.	incinerator	9.00E+00	513,662	3,566,083	8.00	1,000.00	0.03	18.50
Beaufort	BEA12	Daufuskie Island P&H Inc.	Air Curtain Incinerator	7.00E-01	511,295	3,552,724	7.42	633.00	5.00	10.09
Berkeley	BER01	Prouvost USA	Boiler 3	3.88E+00	622,554	3,684,017	65.00	375.00	15.00	4.00
Berkeley	BER02	Plusa, Inc. (Prouvost USA)	Boiler 2 Stack	4.23E+00	622,554	3,684,017	65.00	400.00	15.00	3.00
Berkeley	BER03	Bayer Corporation	ID#102, 103, 104,BldgB9-2	1.00E-02	600,041	3,649,772	101.00	105.00	53.00	2.33
Berkeley	BER04	Bayer Corporation	ID#600 & 601, C9-1/2	1.60E-01	600,041	3,649,772	50.00	122.00	52.00	3.50
Berkeley	BER05	Bayer Corporation	ID#552, C8-1/2	8.00E-02	600,041	3,649,772	50.00	80.00	0.03	0.66
Berkeley	BER06	Albany Int'l-Press Fabrics	Boiler #2	-2.91E+01	599,913	3,697,883	30.00	449.30	19.52	2.00
Berkeley	BER07	Albany Int'l-Press Fabrics	Boiler #3	3.43E+01	599,929	3,697,840	77.76	421.00	111.88	1.00
Berkeley	BER08	Albany Int'l-Press Fabrics	Boiler #4	-2.18E+01	599,976	3,697,836	32.00	601.00	17.06	2.00
Berkeley	BER09	Albany Int'l-Press Fabrics	Boiler #5	9.10E+00	599,925	3,697,847	75.79	170.30	21.52	2.08
Berkeley	BER10	Naval Weapons Station	Bldg 3107 Boiler #1	5.89E+00	595,791	3,641,505	24.00	350.00	0.03	1.00
Berkeley	BER11	Naval Weapons Station	Bldg 3107 Boiler #2	5.89E+00	595,788	3,641,501	24.00	350.00	0.03	1.00
Berkeley	BER12	Naval Weapons Station	Paint Booth Bldg 1659	6.80E-03	599,175	3,646,250	30.50	70.00	43.31	3.50
Berkeley	BER13	Alcoa - Mt. Holly	Baked Carbon Plant	6.74E+01	588,706	3,657,364	201.00	176.00	86.84	4.70
Berkeley	BER14	Alcoa - Mt. Holly	Scrubber Lines	8.49E+02	588,255	3,657,328	200.00	176.00	77.00	10.50
Berkeley	BER15	Alcoa - Mt. Holly	Cast House #50	9.00E-03	588,053	3,657,153	60.00	72.00	40.27	4.00
Berkeley	BER16	Alcoa - Mt. Holly	Cast House #51	8.10E-02	588,064	3,657,126	67.00	500.00	40.00	3.00
Berkeley	BER17	Alcoa - Mt. Holly	Cast House #52	4.30E-02	588,088	3,657,089	57.00	200.00	0.03	2.00
Berkeley	BER19	Alcoa - Mt. Holly	Diesel Fire Pump	5.20E-01	588,302	3,657,048	20.00	300.00	89.37	0.33
Berkeley	BER20	The Gates Rubber Company	Boiler #3	1.06E+01	593,399	3,673,883	50.00	400.00	36.47	2.00
Berkeley	BER21	The Gates Rubber Company	Coaters/Oxidize	1.60E-01	593,514	3,674,030	63.00	518.00	31.13	2.25
Berkeley	BER22	The Gates Rubber Company	Evaporator	2.27E+00	593,398	3,673,970	25.00	72.00	0.03	1.75
Berkeley	BER23	BP-Amoco Cooper River	ITEGEN	1.60E+00	604,672	3,648,420	9.00	1,187.00	217.40	0.66
Berkeley	BER24	BP-Amoco Cooper River	Boilers #1&2	-1.11E+03	604,836	3,648,885	100.00	290.00	38.90	7.00
Berkeley	BER25	BP-Amoco Cooper River	Boilers #3&4	9.52E+01	604,836	3,648,824	100.00	270.00	8.30	8.00
Berkeley	BER26	BP-Amoco Cooper River	UT Compressor #2	2.33E+00	604,749	3,648,875	10.00	770.00	212.90	0.98
Berkeley	BER27	BP-Amoco Cooper River	#1 Ox Compressors 1,2,3&4	3.36E+01	604,512	3,649,008	10.00	775.00	342.80	0.52
Berkeley	BER28	BP-Amoco Cooper River	#2 Ox Emergency Generator #3	1.42E+00	604,382	3,648,765	6.00	986.00	194.00	0.49
Berkeley	BER29	BP-Amoco Cooper River	WWT Compressors L-1 & L-2	6.00E+00	603,502	3,648,708	10.00	775.00	342.80	0.49
Berkeley	BER30	Santee Cooper - Cross	Units 1-4	5.00E+03	582,614	3,692,405	488.00	122.00	25.00	69.00
Berkeley	BER31	Santee Cooper - Cross	Unit 2	3.12E+03	582,614	3,692,405	600.00	150.00	70.00	22.00
Berkeley	BER32	JW ALUMINUM	MELT FURNACE #1-4	8.00E-02	588,658	3,654,970	85.00	1,622.00	52.10	4.50
Berkeley	BER33	JW ALUMINUM	HOLD FURNACE #1-3	5.40E+01	588,658	3,654,977	70.00	467.00	32.10	2.00
Berkeley	BER34	JW ALUMINUM	Hold Furnace #4-5	2.00E-02	588,583	3,654,977	70.00	467.00	32.10	2.00
Berkeley	BER35	JW ALUMINUM	ANNEALING #1-10	1.00E-01	588,705	3,655,022	45.00	275.00	16.70	1.67
Berkeley	BER36	JW ALUMINUM	ANNEALING #11	1.00E-02	588,851	3,655,022	49.00	275.00	10.25	2.17
Berkeley	BER37	Santee Cooper	Incinerator	-6.90E-01	595,255	3,673,829	20.00	950.00	0.03	0.83
Berkeley	BER38	S.C. Pipeline	Backup	1.00E-02	599,600	3,654,100	24.93	159.50	0.03	2.00
Berkeley	BER39	Berkeley Co. Water & Sanitatio	emergency generator	8.18E+00	596,817	3,646,583	16.00	1,053.00	176.00	1.33
Berkeley	BER40	Nucor Steel	Baghouse	9.75E+01	603,968	3,652,492	175.00	275.00	95.34	21.10
Berkeley	BER41	Nucor Steel	Baghouse	3.25E+01	604,065	3,652,374	150.00	150.00	68.27	17.00
Berkeley	*BER42*	*Nucor Steel*	*Melt Shop Roof Monitor*	*9.50E-02*	*604,250*	*3,652,302*	*126.50*	*16.37*	*58.14*	
Berkeley	*BER43*	*Nucor Steel*	*Tundish Dryer Monitor*	*9.50E-03*	*604,259*	*3,652,239*	*126.50*	*1.41*	*58.14*	
Berkeley	*BER44*	*Nucor Steel*	*Beam Mill Roof Monitor*	*6.00E-02*	*604,165*	*3,652,211*	*126.50*	*8.17*	*58.14*	
Berkeley	BER45	Nucor Steel	Tunnel Furnace 1 Stack 1	4.80E-02	604,327	3,652,308	112.50	1,050.00	27.00	7.51
Berkeley	BER46	Nucor Steel	Tunnel Furnace 1 Stack 2	3.02E-02	604,415	3,652,281	112.50	1,050.00	27.00	7.51
Berkeley	BER47	Nucor Steel	Tunnel Furnace 2	4.80E-02	604,311	3,652,245	112.50	1,050.00	27.00	7.51
Berkeley	BER48	Nucor Steel	Reheat Furnace	1.11E-01	604,206	3,652,097	150.00	1,000.00	41.10	7.51
Berkeley	*BER49*	*Nucor Steel*	*Tunnel Furnace No. 1 Roof Monitor*	*1.20E-02*	*604,370*	*3,652,272*	*55.00*	*14.60*	*23.26*	
Berkeley	*BER50*	*Nucor Steel*	*Tunnel Furnace No. 2 Roof Monitor*	*1.20E-02*	*604,365*	*3,652,253*	*55.00*	*14.60*	*23.26*	
Berkeley	BER51	Nucor Steel	Pickle Line #1 Boiler	1.80E-02	604,604	3,652,025	74.90	550.00	35.00	2.00
Berkeley	*BER52*	*Nucor Steel*	*Annealing Furnaces*	*7.22E-02*	*604,596*	*3,651,944*	*85.50*	*1.87*	*37.80*	
Berkeley	BER53	Nucor Steel	Galvanizing Furnace Stack	5.00E-02	604,520	3,651,882	130.00	700.00	24.70	7.00
Berkeley	BER54	Nucor Steel	Pickle Line No. 2 Boilers	1.83E-02	604,748	3,652,018	75.00	550.00	35.00	2.00
Berkeley	BER55	Nucor Steel	Vacuum Tank Degasser Boiler	3.00E-02	604,286	3,652,310	141.50	450.00	39.63	3.00
Berkeley	BER56	MG Industries	Vaporization Boiler	1.20E-02	605,750	3,651,950	12.50	400.00	0.03	3.67
Berkeley	BER57	Fortifiber Coporation	Gas Fired Paper	2.00E-03	589,288	3,827,842	30.00	330.00	133.60	0.50
Berkeley	BER58	Fortifiber Coporation	Air Dryer	6.00E-03	609,501	3,643,143	30.00	471.00	88.87	1.42
Berkeley	BER59	Santee River Rubber Co.	Air Dryer	1.00E-03	609,501	3,643,143	70.00	173.00	0.03	3.46
Berkeley	BER60	Santee River Rubber Co.	Primary Dryer	1.00E-03	609,501	3,643,143	70.00	134.00	0.03	4.63
Berkeley	BER61	Santee River Rubber Co.	Secondary Dryer	1.00E-03	609,501	3,643,143	60.00	123.00	0.03	3.54
Berkeley	BER62	Corning, Inc.	Furnaces 1 and 2 (EP-2)	1.08E-02	585,500	3,654,000	75.00	225.00	98.42	4.80
Berkeley	BER63	Corning, Inc.	Furnace 3 (EP-1)	5.40E-03	585,500	3,654,000	75.00	225.00	98.75	3.40
Berkeley	BER64	Corning, Inc.	Annealing Furnaces & Supply Heaters	1.30E-02	585,500	3,654,000	45.00	350.00	58.30	3.30
Berkeley	BER65	Corning, Inc.	Emergency Generator (EP-7)	9.52E-01	585,500	3,654,000	43.00	900.00	152.20	0.67
Berkeley	BER66	Corning, Inc.	Boiler 1 (EP-8)	1.14E-02	585,500	3,654,000	50.00	450.00	22.00	2.17
Berkeley	BER67	Corning, Inc.	Boiler 2 (EP-9)	1.14E-02	585,500	3,654,000	50.00	450.00	22.00	2.17
Berkeley	*BER68*	*Detyens Shipyard*	*3 mobile hydroblasting units*	*5.39E-01*	*609,511*	*3,643,494*	*19.00*	*70.01*	*423.00*	*-38.90*
Berkeley	BER69	Terranova Forest Products	9.0 MMBut/hr gas-fired Curing Oven	4.20E-03	601,316	3,640,838	20.00	100.00	0.03	2.00
Berkeley	BER70	DAK Americas LLC	Boiler 1	1.41E+00	598,857	3,658,125	150.00	320.00	35.22	5.00
Berkeley	BER71	DAK Americas LLC	Boiler 2	1.41E+00	598,851	3,658,142	150.00	320.00	42.68	5.00
Berkeley	BER72	DAK Americas LLC	Vaporizors 1-4	6.45E+01	598,875	3,658,116	150.00	629.00	15.03	4.27
Berkeley	BER73	Williams Technology	Dyno1 - Engine Testing	1.00E-02	580,517	3,654,949	15.00	125.00	0.03	0.17
Berkeley	BER74	Williams Technology	Dyno2 - Engine Testing	1.00E-02	580,520	3,654,946	15.00	125.00	0.03	0.17
Calhoun	CAL01	Columbia Energy Center	Auxiliary Boiler 1&2	4.20E+01	498,356	3,747,530	150.00	350.00	69.90	5.50
Calhoun	CAL02	Columbia Energy Center	Auxiliary Boiler 3	3.17E+01	498,375	3,747,503	150.00	307.00	66.30	7.00
Calhoun	CAL03	Columbia Energy Center	Combustion Turbine 1&2	1.98E+02	498,312	3,747,499	200.00	248.00	64.60	19.00
Charleston	CHA01	MeadWestvaco	No. 4 Lime Kiln	3.69E+00	596,565	3,640,468	114.00	152.00	26.20	5.84
Charleston	CHA02	MeadWestvaco	No. 5 Lime Kiln	2.16E+01	596,489	3,640,493	213.00	349.00	58.53	6.00
Charleston	CHA03	MeadWestvaco	KREC004 Recovery Boiler #1	4.78E+02	596,666	3,640,329	411.00	327.00	68.40	11.40
Charleston	CHA04	MeadWestvaco	KREC005 East SDTV #1	7.38E+00	596,680	3,640,335	258.00	170.00	29.50	3.94
Charleston	CHA05	MeadWestvaco	KREC006 West SDTV #1	7.38E+00	596,669	3,640,342	258.00	170.00	29.50	3.94
Charleston	CHA06	MeadWestvaco	KWY026 Temp Mobile Chip Screen	8.73E-02	596,382	3,640,520	7.55	350.00	0.03	0.17
Charleston	CHA07	MeadWestvaco	KWY041 Temp Mobile Bark Screen	8.73E-02	596,169	3,640,389	7.55	350.00	0.03	0.17
Charleston	CHA08	MeadWestvaco	TALLSTK	-9.40E+02	596,798	3,640,316	301.00	335.00	104.00	11.00
Charleston	CHA09	MeadWestvaco	PB5 Power Boiler 5	-6.98E+00	596,829	3,640,328	157.00	170.00	87.90	7.50
Charleston	CHA10	Rhodia	Boiler #1	1.27E+00	596,761	3,633,258	40.00	350.00	46.10	2.00
Charleston	CHA11	Rhodia	Boiler #2	7.08E+01	596,764	3,633,250	65.00	350.00	12.00	4.53
Charleston	CHA12	Rhodia	Thermal Oxidizer Unit	3.40E+00	596,930	3,633,159	63.00	136.00	24.90	3.02
Charleston	CHA13	Rhodia	old Boiler #1&2	-1.28E+02	596,764	3,633,250	65.00	350.00	21.00	4.53

Table A-1. Regional Inventory Sources

County	ID	Company Name	Stack Details	SO_2 Emissions (lb/hr)	UTM East (m)	UTM North (m)	Height (ft)	Temp °F	Modeled Velocity (ft/s)	Diameter (ft)
Charleston	CHA14	Allied Terminal	Superior Boiler	2.18E+01	598,201	3,632,234	58.30	480.00	26.32	1.67
Charleston	CHA15	Allied Terminal	Daniels Heater	1.31E+01	598,210	3,632,268	50.00	750.00	33.10	2.50
Charleston	CHA16	RM Engineered Products	Boiler 1	2.04E+01	595,779	3,638,620	51.00	413.00	46.40	2.33
Charleston	CHA17	RM Engineered Products	Boiler 2	-7.36E+01	595,786	3,638,628	70.00	500.00	15.20	4.00
Charleston	CHA18	Charleston AFB	Boiler #4	1.19E+00	588,399	3,640,643	42.00	300.00	0.03	1.20
Charleston	CHA19	Charleston AFB	Boiler #6	2.13E+00	588,399	3,640,643	19.00	300.00	0.03	1.16
Charleston	CHA20	Charleston AFB	Boiler #7	1.17E+00	588,399	3,640,643	33.00	425.00	22.50	1.00
Charleston	CHA21	Charleston AFB	Boiler #8	2.00E-03	588,399	3,640,643	28.00	300.00	0.03	0.83
Charleston	CHA22	Charleston AFB	545 Engine Test Cell	4.00E+00	588,399	3,640,643	48.00	188.00	55.10	30.38
Charleston	CHA23	Charleston AFB	hot water heater	8.00E-03	589,177	3,640,573	28.00	450.00	34.00	1.67
Charleston	CHA24	Charleston AFB	Air Handler 1 Boiler	9.00E-03	590,302	3,640,578	94.00	130.00	0.03	1.67
Charleston	CHA25	Charleston AFB	Air Handler 2 Boiler	9.00E-03	589,003	3,640,535	94.00	130.00	0.03	1.67
Charleston	CHA26	Medical University of SC	Old S-1 Boilers	-2.22E+02	598,460	3,627,790	150.00	457.00	0.03	6.00
Charleston	CHA27	Medical University of SC	S-1 Boilers	5.10E+01	598,480	3,627,765	65.00	475.00	0.03	3.67
Charleston	CHA28	Medical University of SC	S-7&8 StromBldg Superior Boiler B770-	1.36E+01	598,500	3,627,740	182.00	450.00	0.03	2.00
Charleston	CHA29	Medical University of SC	SAC-1 Boiler	3.20E+00	598,460	3,627,690	95.00	350.00	36.80	1.00
Charleston	CHA30	Medical University of SC	HCC-1&2 Boiler	1.17E+01	598,540	3,627,700	102.00	350.00	0.03	1.67
Charleston	CHA31	Medical University of SC	BSB-2&3 Boiler	3.44E+00	598,560	3,627,690	88.00	330.00	24.60	3.00
Charleston	CHA32	Medical University of SC	S-13, S-14, S-15 Boilers	2.59E+00	598,585	3,627,580	97.70	250.00	42.50	1.00
Charleston	CHA33	City of Chas. Sludge Inciner	Incineration scrubber Exhaust	1.10E+00	596,795	3,624,871	45.00	155.00	41.67	4.00
Charleston	CHA34	GS Roofing Products	RTO	1.90E-02	593,014	3,634,152	75.00	494.00	43.07	2.50
Charleston	CHA35	Kinder Morgan Bulk Terminals	Boiler	4.22E+00	599,450	3,632,658	40.00	440.00	9.84	3.00
Charleston	CHA36	SCE&G - Hagood	Combustion Turbine	6.30E+02	597,038	3,632,312	125.00	977.00	150.00	16.00
Charleston	CHA37	SCE&G - Hagood	Reduction: Boiler 1	-7.20E+02	597,038	3,632,342	125.00	350.00	49.10	11.00
Charleston	CHA38	SCE&G - Hagood	Reduction: Boiler 2	-7.20E+02	597,038	3,632,342	125.00	350.00	49.10	11.00
Charleston	CHA39	SCE&G - Hagood	Reduction: Boiler 3	-1.48E+03	597,038	3,632,342	125.00	340.00	43.20	11.00
Charleston	CHA40	Charleston Packaging Co.	Boiler 1	6.00E-03	596,696	3,634,940	38.00	275.00	0.03	2.00
Charleston	CHA41	Charleston Packaging Co.	Boiler 2	6.00E-03	596,696	3,634,940	38.00	275.00	0.03	2.00
Charleston	CHA42	Siebe North, Inc.	boiler 1	7.50E-01	593,382	3,634,366	28.40	400.00	0.03	1.64
Charleston	CHA43	Charleston Steel & Metal Co.	EP01	6.40E+00	598,716	3,630,618	30.00	1,900.00	13.70	2.00
Charleston	CHA44	Kinder Morgan Bulk Terminals	Dryer/Baghouse	3.00E-03	595,953	3,639,214	40.00	180.00	41.70	5.10
Charleston	CHA45	Lockheed Martin Aeronautical	1950&1951	-3.40E+00	592,852	3,634,372	37.00	430.00	0.03	0.70
Charleston	CHA46	Lockheed Martin Aeronautical	1964 & 1965	-2.00E-02	592,907	3,634,341	34.00	340.00	0.03	6.80
Charleston	CHA47	Lockheed Martin Aeronautical	1966	-4.00E-03	592,916	3,634,285	34.00	740.00	0.03	6.80
Charleston	CHA48	Roper Hospital	S-01&2 Boiler 1&2	3.20E+00	598,330	3,627,700	70.00	375.53	29.53	2.00
Charleston	CHA49	Roper Hospital	S-03 Generator 9&10	1.47E+00	598,300	3,627,650	33.00	1,018.00	0.03	0.67
Charleston	CHA50	R.H. Johnson VA Medical Center	Boiler 1,2,3	6.00E+00	597,991	3,627,723	70.00	425.00	45.00	2.30
Charleston	CHA51	R.H. Johnson VA Medical Center	Incinerator	1.37E+00	597,991	3,627,623	80.00	1,318.00	33.76	2.10
Charleston	CHA52	Moore Drums	Reclam Furnace	8.10E-01	592,909	3,634,604	51.50	500.00	60.84	2.21
Charleston	CHA53	Moore Drums	Fuel Oil Boiler	-1.67E+00	593,039	3,634,534	25.75	375.00	37.89	0.92
Charleston	CHA54	Moore Drums	Naturlgas boilr	1.00E-02	593,045	3,634,536	30.33	395.00	7.01	1.96
Charleston	CHA55	Tarmac America	Steam Generator	1.00E+00	599,200	3,623,878	22.00	300.00	0.03	0.25
Charleston	CHA56	South Carolina Farm Bureau	Cambell Dryer	-1.50E-02	597,467	3,641,286	70.00	160.00	0.03	6.79
Charleston	CHA57	Trident Medical Center	Boiler 1&2	2.10E+00	586,593	3,648,706	40.00	420.00	40.30	2.00
Charleston	CHA58	Broyhill Furniture	14MMBut/hr Boiler	7.00E-02	578,565	3,652,796	57.00	500.00	22.00	3.50
Charleston	CHA59	MeadWestvaco Chemical Division	Boiler #9	5.48E+00	596,337	3,640,139	35.10	650.00	0.03	1.84
Charleston	CHA60	MeadWestvaco Chemical Division	Spray Dryer	2.30E+00	596,368	3,640,184	85.00	140.00	40.70	6.00
Charleston	CHA61	MeadWestvaco Chemical Division	Kettle Thermal Oxidizer	1.25E+00	596,432	3,640,044	100.00	190.00	65.00	3.00
Charleston	CHA62	MeadWestvaco Chemical Division	Process Tank Point Sources	-7.90E-02	596,320	3,640,228	45.92	87.80	0.57	1.35
Charleston	CHA63	MeadWestvaco Chemical Division	Poly Process Tank Point Sources	-1.75E+01	596,344	3,640,187	32.00	87.80	0.03	0.33
Charleston	CHA64	Siebe-North, Inc.-Butyl 2	Boiler 1&2	8.52E+00	592,008	3,636,245	38.32	400.00	29.83	1.33
Charleston	CHA65	SC Department of Natural Resources	two 5.5 MMBtu/hr boiler	5.49E+00	602,891	3,624,118	25.00	340.00	0.03	34.05
Charleston	CHA66	North Charleston Sewer Dist.	incinerator	7.40E+00	598,677	3,632,593	55.25	98.00	28.49	1.87
Charleston	CHA67	Foster Wheeler	Boiler SG-201A	8.00E+01	597,800	3,634,000	249.00	300.00	52.00	5.34
Charleston	CHA68	The Scotts Company	Thermal Oxidizer 1	2.13E+00	587,898	3,642,750	47.00	602.00	39.60	3.00
Charleston	CHA69	The Scotts Company	Thermal Oxidizer 2	1.01E+01	587,894	3,642,709	50.00	350.00	45.12	3.17
Charleston	CHA70	Englehard Corp - Mearl LLC	Mica Heat Treating Furnace (EP01)	4.50E-03	587,708	3,642,987	38.00	1,300.00	8.00	3.00
Charleston	CHA71	Englehard Corp - Mearl LLC	Steam Boiler No. 1 (EP05)	7.50E-03	587,708	3,642,987	38.00	500.00	40.00	2.80
Charleston	CHA72	ExxonMobil	Boiler	6.34E+00	598,745	3,631,800	55.00	450.00	32.70	1.67
Charleston	CHA73	Deytens Shipyards	Boiler #2	3.10E+00	596,588	3,636,368	25.00	610.00	8.76	2.00
Charleston	CHA74	Deytens Shipyards	Boiler #3	1.36E+00	596,732	3,636,547	12.00	580.00	21.23	1.00
Charleston	CHA75	Bon Secours St. Francis Xavier	Boiler 1&2	1.76E+00	589,814	3,630,588	44.50	445.00	30.38	2.00
Charleston	CHA76	Bon Secours St. Fancis Xavier	Generator 1&2	9.00E-01	589,714	3,629,588	50.00	1,026.00	227.25	0.83
Charleston	CHA77	Bon Secours St. Francis Xavier	Generator 3	4.93E-01	590,000	3,630,500	55.00	1,026.00	352.00	0.70
Charleston	CHA78	City of Charleston-Hanahan	diesel generator 1&2	8.40E-01	591,091	3,643,058	24.00	1,050.00	424.20	0.67
Charleston	CHA79	City of Charleston-Hanahan	diesel generator 6&7	2.38E+00	591,091	3,643,058	32.80	955.00	318.47	0.50
Charleston	CHA80	Cogen South LLC	Main Boiler	4.02E+02	596,560	3,640,005	403.00	161.00	56.40	11.00
Charleston	CHA81	Cogen South LLC	Aux Boilers	3.11E+02	596,492	3,640,081	243.00	370.00	68.30	10.00
Charleston	CHA82	Palmetto Lime LLC	Kiln stack	3.68E+00	599,290	3,632,145	295.50	355.00	61.00	7.00
Charleston	CHA83	Charleston Technical Center	CTC Boiler	3.67E+00	595,998	3,640,015	63.50	300.00	41.34	1.57
Charleston	CHA84	Green Oasis Environmental	EE1	5.04E+00	599,000	3,631,800	40.00	678.00	21.50	1.65
Charleston	CHA85	Mount Pleasant Waterworks	900 kW Generator	4.88E+00	609,954	3,630,490	20.00	897.00	0.03	79.29
Charleston	CHA86	Mount Pleasant Waterworks	600 kW Generator	3.25E+00	609,954	3,630,490	18.00	935.00	0.03	101.21
Charleston	CHA87	Avebe (SC)	Boiler	1.00E-02	587,624	3,644,733	30.00	400.00	21.22	1.50
Charleston	CHA88	Avebe (SC)	Air Heater	1.00E-02	587,624	3,644,733	30.00	580.00	33.09	2.20
Charleston	CHA89	College of Charleston	Boiler 1	7.54E+00	600,095	3,627,983	43.00	430.00	36.61	2.83
Charleston	CHA90	College of Charleston	Boiler 2	7.54E+00	600,100	3,627,990	43.00	430.00	36.61	2.83
Charleston	CHA91	Mt. Pleasant Waterworks	WG-7 peak shaving generator	1.13E+00	609,132	3,631,867	14.00	935.00	0.03	0.50
Charleston	CHA92	American Tank Fabrication Co.	TF-F1	1.00E-02	596,681	3,636,603	54.00	400.00	0.03	3.33
Charleston	CHA93	Heritage Synfuel Binders	Hot Oil Heater	2.45E+00	598,547	3,631,941	35.00	400.00	13.00	1.17
Charleston	CHA94	Cummins MerCruiser Diesel, LLC	ETC1015	1.61E+00	591,061	3,634,217	46.92	500.00	22.34	0.49
Charleston	CHA95	Cummins MerCruiser Diesel, LLC	ETC1618	1.34E+00	591,043	3,634,209	46.92	500.00	22.34	0.82
Charleston	CHA96	Mt. Pleasant Waterworks Plant #4	Generator	1.25E+00	615,507	3,638,222	17.50	935.00	84.00	1.00
Charleston	CHA97	Vought Aircraft Industries, Inc.	Autoclave Stacks 1,2,3	2.64E-02	590,199	3,637,620	69.00	500.00	82.00	2.00
Charleston	CHA98	Holset Engineering	Test Cell 1	9.80E-02	582,213	3,647,898	45.00	500.00	176.00	0.50
Charleston	CHA99	Holset Engineering	Test Cell 2	9.80E-02	582,213	3,647,898	45.00	500.00	176.00	0.50
Charleston	CHA100	Holset Engineering	Test Cell 3	9.80E-02	582,213	3,647,898	45.00	500.00	176.00	0.50
Charleston	CHA101	Holset Engineering	Test Cell 4	9.80E-02	582,213	3,647,898	45.00	500.00	176.00	0.50
Charleston	CHA102	Holset Engineering	Test Cell 5	9.80E-02	582,213	3,647,898	45.00	500.00	176.00	0.50
Charleston	CHA103	Holset Engineering	Test Cell 6	4.14E-01	582,213	3,647,898	45.00	500.00	234.70	0.50
Chesterfield	CHE01	Dixie Yarns- Caroknit Plant	Boiler #1	7.07E+01	556,189	3,824,502	50.00	550.00	23.00	3.94
Chesterfield	CHE02	Dixie Yarns- Caroknit Plant	Dryer #6	5.60E-03	556,189	3,824,502	28.00	248.00	52.00	1.94
Chesterfield	CHE03	TALLEY METALS TECHNOLOGY, INC.	BOILERS 1 AND 2 (stk 8)	1.20E-01	576,340	3,810,152	35.10	400.00	0.03	2.00
Chesterfield	CHE04	Talley Metals Technology	Soaking Furnace (stk 22)	1.33E-01	573,524	3,810,052	46.00	1,400.00	38.11	3.50
Chesterfield	CHE05	Talley Metals Technology,Inc.	Boiler 3 (stk 13)	9.90E-02	576,333	3,810,157	40.00	1,400.00	38.11	1.84
Chesterfield	CHE06	Talley Metals Technology,Inc.	HTF-7 (stk 19/20)	1.44E-01	576,425	3,810,102	35.00	600.00	0.03	4.00
Chesterfield	CHE07	Talley Metals Technology,Inc.	HT Furnaces 1-6(stk 18)	1.32E-02	576,398	3,810,118	46.00	512.00	38.11	3.50
Chesterfield	CHE08	Talley Metals Technology,Inc.	HTF 8, RH Furnace 1(stk 31)	2.20E-02	576,368	3,810,158	40.00	783.00	38.11	3.50
Chesterfield	CHE09	Talley Metals Technology,Inc.	RHF 2, BBU 2, CBU 1-2(stk 32)	9.80E-03	576,369	3,810,155	40.00	783.00	38.11	3.50
Clarendon	CLA01	Aircap Industries	boilers	-1.72E+02	576,339	3,727,618	42.00	385.00	47.70	2.00
Darlington	DAR01	Nucor Steel	Baghouse	-2.85E+02	601,809	3,804,275	75.00	200.00	74.10	21.00

Table A-1. Regional Inventory Sources

County	ID	Company Name	Stack Details	SO_2 Emissions (lb/hr)	UTM East (m)	UTM North (m)	Height (ft)	Temp °F	Modeled Velocity (ft/s)	Diameter (ft)
Darlington	DAR02	Nucor Steel Darlington	SILO-1	2.85E+02	601,813	3,804,543	113.00	68.00	30.10	0.75
Darlington	DAR03	Nucor Steel	Reheat Furnace 1	1.11E-01	601,570	3,804,053	75.00	689.00	60.40	5.00
Darlington	DAR04	Nucor Steel	Reheat Furnace 2	1.11E-01	601,572	3,803,963	75.00	689.00	60.40	5.00
Darlington	DAR05	Nucor Steel	Reheat Furnace 3	1.11E-01	601,719	3,804,080	75.00	689.00	60.40	5.00
Darlington	*DAR06*	*Nucor Steel*	*Melt Shop 3 Roof Monitors*	*5.88E-01*	*601,769*	*3,804,158*	*123.60*	*24.00*	*51.10*	
Darlington	*DAR07*	*Nucor Steel*	*Old Melt Shop & Billet Cutting Roof*	*1.96E-02*	*601,639*	*3,804,117*	*63.00*	*61.00*	*29.30*	
Darlington	*DAR08*	*Nucor Steel*	*Space Heaters*	*2.40E-02*	*601,202*	*3,804,201*	*56.00*	*1.87*	*23.29*	
Darlington	DAR09	Carolina Power & Light	CT12	3.15E+02	576,344	3,808,662	60.00	1,010.00	106.00	20.00
Darlington	DAR10	Carolina Power & Light	CT13	3.15E+02	576,305	3,808,647	60.00	1,010.00	106.00	20.00
Darlington	DAR11	Galey & Lord Industries, Inc.	Dyeing Dept II	9.82E-03	606,458	3,821,150	39.00	120.00	0.03	2.50
Darlington	DAR12	Galey & Lord Industries, Inc.	Finishing Dept I	3.50E-03	606,665	3,820,843	36.52	80.30	0.03	1.71
Darlington	DAR13	Galey & Lord Industries, Inc.	Finishing Dept II	-2.40E-02	606,395	3,821,100	40.00	300.00	0.03	1.31
Darlington	DAR14	Sonoco Products	Kiln/Thermal Oxidizer	1.12E+01	585,901	3,805,336	101.00	400.00	61.00	3.50
Darlington	DAR15	Sonoco Products	Boiler #9	2.81E+01	585,889	3,805,210	150.00	230.00	43.40	4.75
Darlington	DAR16	Wellman -- Palmetto Plant	Dowtherm 6	5.00E-02	609,754	3,792,534	100.00	350.00	31.00	12.00
Darlington	DAR17	Wellman, Inc.	Dowtherm 7	5.00E-02	609,804	3,792,578	82.00	300.00	50.02	3.05
Darlington	DAR18	Wellman, Inc.	Common Stack	1.02E+02	609,810	3,792,566	100.00	350.00	31.00	12.00
Darlington	DAR19	Wellman, Inc.	boiler 4	6.00E-02	609,839	3,792,784	75.00	379.00	76.00	3.94
Darlington	DAR20	PowerSecure, Inc.	GEN1 - Generator	1.06E+00	609,179	3,792,693	16.50	716.00	255.58	1.18
Dorchester	DOR01	Giant Cement	Main Baghouse/Bypass Vent	5.40E+02	552,133	3,678,232	295.00	230.00	50.23	14.20
Dorchester	DOR02	Giant Cement	Kilns #4 & 5	-8.90E+02	552,147	3,678,286	174.90	260.00	59.06	9.84
Dorchester	DOR03	Giant Cement	Kilns #2 & 3	-6.82E+02	551,906	3,678,525	163.10	280.00	59.06	9.84
Dorchester	DOR04	Giant Cement	Marl Dryer Scrubber	-3.25E+01	551,934	3,678,397	49.90	160.00	69.23	3.61
Dorchester	DOR05	Blue Circle Cement	Stack #1	1.07E+02	551,000	3,676,300	100.00	220.00	70.00	10.00
Dorchester	DOR06	Blue Circle Cement	Stack #36	5.33E+01	551,017	3,676,238	115.00	180.00	11.91	6.00
Dorchester	DOR07	Westvaco Lumber Mill	Kiln 3-Stack 3C	3.70E-01	575,303	3,654,922	26.00	240.00	0.03	0.56
Dorchester	DOR08	Westvaco Lumber Mill	Kiln 4-Stack 5	6.03E-01	575,294	3,654,911	30.00	240.00	0.03	51.57
Dorchester	DOR09	Robert Bosch Corporation	Boiler 5	2.56E+00	584,008	3,641,260	33.14	305.00	17.06	1.84
Dorchester	DOR10	Robert Bosch Corporation	Boiler 6	2.56E+00	584,012	3,641,258	33.14	305.00	17.06	1.84
Dorchester	DOR11	Showa Denko Carbon	Carbottom furn. Incinerator (S7)	3.05E+01	561,220	3,661,343	80.00	1,450.00	200.00	7.92
Dorchester	DOR12	Showa Denko Carbon	Graphitizing (S22)	1.33E+02	561,164	3,661,344	190.00	190.00	75.45	7.50
Dorchester	*DOR13*	*Showa Denko Carbon*	*roof moniters (VS1-6)*	*4.43E+01*	*561,117*	*3,661,336*	*76.00*	*43.20*	*31.20*	
Dorchester	DOR14	Summerville Medical Center	boiler 1	1.20E+00	579,022	3,647,533	26.20	396.00	24.00	1.00
Dorchester	DOR15	Summerville Medical Center	boiler 2	1.20E+00	579,022	3,647,533	26.20	396.00	24.00	1.00
Dorchester	DOR16	Fibron International Corp	FiberizgProcess1	7.50E-03	573,372	3,656,366	52.00	190.00	78.70	4.00
Dorchester	DOR17	Fibron International Corp	FiberizgProcess2	7.50E-03	573,362	3,656,355	52.00	190.00	78.70	4.00
Dorchester	DOR18	Fibron International Corp	FiberizgProcess3	7.50E-03	573,350	3,656,342	52.00	190.00	78.70	4.00
Dorchester	DOR19	Fibron International Corp	FiberizgProcess4	7.50E-03	573,339	3,656,330	52.00	190.00	78.70	4.00
Dorchester	DOR20	Fibron International Corp	FiberizgProcess5	7.50E-03	573,328	3,656,318	52.00	190.00	78.70	4.00
Dorchester	DOR21	Chamber Oakridge Landfill	flare	1.50E-01	558,610	3,666,531	22.00	1,400.00	40.00	0.67
Dorchester	DOR22	Dausey	boiler	1.36E+00	539,542	3,671,808	18.00	450.00	0.03	1.17
Dorchester	DOR23	Raisio Staest US Inc	Steam Boiler	3.00E-02	573,000	3,657,000	30.00	550.00	40.00	2.00
Dorchester	DOR24	Raisio Staest US Inc	Hot Oil System	1.00E-02	573,000	3,657,000	30.00	630.00	22.00	1.67
Dorchester	DOR25	Cemplank Inc.	0021 (Boiler)	1.19E+01	572,861	3,657,278	44.00	469.00	36.75	2.33
Dorchester	DOR26	Souteastern Soil Recovery	Soil Treatment Unit	1.06E+01	573,364	3,655,741	30.70	300.00	46.40	4.00
Dorchester	DOR27	Banks Construction Co.	Drum Mixer/Dryer	2.32E+01	573,400	3,665,700	30.00	240.00	88.70	3.00
Dorchester	DOR28	Banks Construction Co.	Hot Oil Heater	1.05E+00	573,400	3,665,700	14.00	600.00	10.80	1.00
Florence	FLO01	Talon, Inc.	boiler 1 - stack 17	-7.85E+01	614,192	3,746,291	43.92	350.00	37.20	3.33
Florence	FLO02	Talon, Inc.	boiler 2 - stack 18	-7.85E+01	614,192	3,746,294	46.08	350.00	37.20	3.17
Florence	FLO03	A.C. Monk	steam boiler E	-7.60E+00	615,250	3,748,000	37.70	340.00	27.00	2.00
Florence	FLO04	Stone Container	Recovery Boiler	3.18E+02	632,600	3,779,600	173.00	357.20	101.13	6.17
Florence	FLO05	Stone Container	cogen boiler 4	1.15E+03	632,600	3,779,600	250.00	366.90	64.79	12.00
Florence	FLO06	Stone Container	incinerator	4.50E+00	632,600	3,779,600	100.00	192.00	12.10	3.50
Florence	FLO07	Wellman	Exhaust 113 Scrubber	1.92E+01	643,884	3,744,592	50.00	147.20	51.50	3.50
Florence	FLO08	McLeod Regional Medical Center	boiler 1	-1.08E+01	614,200	3,784,500	30.20	400.00	37.73	2.00
Florence	FLO09	McLeod Regional Medical Center	boiler 2	-1.08E+01	614,200	3,784,500	30.20	400.00	37.73	2.00
Florence	FLO10	McLeod Regional Medical Center	boiler 3	-1.08E+01	614,200	3,784,500	30.20	400.00	37.73	2.00
Florence	FLO11	McLeod Regional Medical Center	boiler 4	4.32E+00	614,200	3,784,500	42.00	400.00	33.79	1.30
Florence	FLO12	McLeod Regional Medical Center	boiler 5	4.32E+00	614,200	3,784,500	42.00	400.00	33.79	1.30
Florence	FLO13	McLeod Regional Medical Center	boiler 7	1.29E+01	614,200	3,784,500	33.00	364.00	40.37	2.00
Florence	FLO14	McLeod Regional Medical Center	boiler 8	1.29E+01	614,200	3,784,500	33.00	364.00	40.37	2.00
Florence	FLO15	McCall Farms	Boiler	4.71E+01	614,855	3,768,666	45.00	350.00	42.00	2.97
Florence	FLO16	McCall Farms	backup boiler	2.59E+01	614,855	3,768,666	40.00	127.00	82.00	2.00
Florence	FLO17	McCall Farms	Boiler#1	7.50E-01	614,855	3,768,666	40.00	400.00	58.00	3.56
Florence	FLO18	McCall Farms	Boiler#1	2.85E+01	614,855	3,768,666	40.00	400.00	58.00	3.56
Florence	FLO19	McCall Farms	Boiler#2	3.93E+01	614,987	3,768,359	36.00	350.00	34.80	2.97
Florence	FLO20	McCall Farms	Boiler#2	3.50E-01	614,855	3,768,666	28.00	350.00	12.40	3.00
Florence	FLO21	McCall Farms	Boiler#3	6.29E+01	614,987	3,768,359	48.00	350.00	39.00	3.00
Florence	FLO22	Roche Carolina	BOILERS	3.00E-01	629,000	3,786,850	51.00	520.00	32.60	4.20
Florence	FLO23	Roche Carolina	Primary Thermal Oxidizer	1.75E+01	628,939	3,786,580	160.00	170.00	40.00	1.67
Florence	FLO24	Roche Carolina	Reserve Thermal Oxidizer	7.80E+00	628,920	3,786,560	50.00	1,000.00	18.90	1.67
Florence	FLO25	Roche Carolina	flare	7.00E-02	629,020	3,786,870	10.00	1,831.00	65.62	2.07
Georgetown	GEO01	Trebol USA, Inc.	Spray Dryer	4.50E-03	633,591	3,700,674	30.50	280.00	21.67	1.00
Georgetown	GEO02	International Paper - Pulp & Paper Mill	power boiler	-4.88E+02	658,200	3,692,500	70.00	550.00	40.00	8.00
Georgetown	GEO03	International Paper - Pulp & Paper Mill	common stack	-3.25E+03	658,150	3,692,600	200.00	470.00	60.00	14.50
Georgetown	GEO04	International Paper - Pulp & Paper Mill	lime kiln	-4.17E+01	658,050	3,692,550	100.00	170.00	32.80	6.00
Georgetown	GEO05	International Paper - Pulp & Paper Mill	lime kiln	-4.16E+01	658,040	3,692,560	100.00	170.00	32.80	6.00
Georgetown	GEO06	International Paper - Pulp & Paper Mill	7&8 power boilers	-9.53E+02	658,180	3,692,540	200.00	470.00	60.00	14.50
Georgetown	GEO07	International Paper - Pulp & Paper Mill	power boiler 1&2	9.57E+02	658,220	3,692,587	280.00	372.00	40.03	17.06
Georgetown	GEO08	International Paper - Pulp & Paper Mill	recovery boiler 1	2.30E+01	658,275	3,692,581	235.00	325.00	56.60	7.87
Georgetown	GEO09	International Paper - Pulp & Paper Mill	recovery boiler 2	5.66E+01	658,217	3,692,622	250.00	160.00	39.70	12.14
Georgetown	GEO10	International Paper - Pulp & Paper Mill	lime kiln 2	4.58E-01	658,105	3,692,592	95.14	158.00	23.00	5.91
Georgetown	GEO11	International Paper - Pulp & Paper Mill	NCG incinerator	9.13E+00	658,128	3,692,719	67.90	181.00	26.40	3.61
Georgetown	GEO12	International Paper - Pulp & Paper Mill	Black Liquor Oxidation Stage 2	1.57E+00	657,900	3,692,840	89.24	178.00	44.82	3.94
Georgetown	GEO13	International Paper - Pulp & Paper Mill	Container Division Sources	3.75E-01	657,900	3,692,840	26.90	410.00	0.03	2.30
Georgetown	GEO14	Georgetown Steel, Inc.	DRI Reduction Furnace	2.00E-02	659,006	3,693,450	30.00	68.00	33.00	1.64
Georgetown	GEO15	Georgetown Steel, Inc.	5	-9.49E+00	659,006	3,693,450	103.00	138.00	14.80	33.50
Georgetown	GEO16	Georgetown Steel, Inc.	Melt Shop Baghouse	3.57E+01	659,006	3,693,450	80.00	181.00	0.03	763.60
Georgetown	GEO17	Georgetown Steel, Inc.	8A	-1.47E+02	659,006	3,693,450	79.20	467.00	36.60	9.42
Georgetown	GEO18	Georgetown Steel, Inc.	PS	2.80E-01	659,006	3,693,450	92.75	291.00	44.90	11.70
Georgetown	GEO19	Santee Cooper - Winyah	Unit 3	1.68E+03	652,778	3,688,824	404.00	161.00	75.10	16.00
Georgetown	GEO20	Santee Cooper - Winyah	Unit 4	1.68E+03	652,719	3,688,819	404.00	161.00	75.10	16.00
Georgetown	GEO21	Santee Cooper - Winyah	Unit 1 Old Stack	-1.73E+03	652,900	3,688,850	404.00	300.00	60.01	18.00
Georgetown	GEO22	International Paper - Sampit Lumber	Gasification Boiler	7.90E-01	644,267	3,698,940	52.00	425.00	42.30	3.00
Georgetown	GEO23	Oneita Industries	PSD-Dryers	1.80E-02	634,095	3,702,924	22.50	250.00	0.03	1.70
Georgetown	GEO24	3V, Inc.	Steam Boiler 501	1.05E+01	652,537	3,691,875	64.00	465.00	32.70	2.50
Georgetown	GEO25	3V, Inc.	Steam BoilerBIF	1.75E+01	652,537	3,691,886	64.00	465.00	54.70	2.50
Georgetown	GEO26	3V, Inc.	Oil Heater	6.28E+00	652,537	3,691,954	52.00	399.00	16.00	2.58
Georgetown	GEO27	Georgetown Memorial Hospital	BOILER #1 & #2	5.61E+01	659,530	3,694,470	45.00	370.00	34.40	1.67
Georgetown	GEO28	Georgetown Memorial Hospital	removed two boilers	-5.40E+00	659,531	3,694,474	30.00	370.00	13.00	1.67
Georgetown	GEO29	Holnam - Georgetown Terminal	Diesel Engine #1	7.00E-02	659,213	3,692,290	13.50	815.00	142.40	0.50

Table A-1. Regional Inventory Sources

County	ID	Company Name	Stack Details	SO_2 Emissions (lb/hr)	UTM East (m)	UTM North (m)	Height (ft)	Temp °F	Modeled Velocity (ft/s)	Diameter (ft)
Georgetown	GEO30	Holnam - Georgetown Terminal	Diesel Engine #2	7.00E-02	659,205	3,692,287	13.50	815.00	142.40	0.50
Georgetown	GEO31	Holnam - Georgetown Terminal	Diesel Engine #3	7.00E-02	659,207	3,692,283	13.50	815.00	142.40	0.50
Georgetown	GEO32	Holnam - Georgetown Terminal	Diesel Engine #4	7.00E-02	659,214	3,692,286	13.50	815.00	142.40	0.50
Georgetown	GEO33	Holnam - Georgetown Terminal	Diesel Engine	1.40E-01	659,192	3,692,282	13.70	840.00	118.70	0.70
Georgetown	GEO34	International Paper - Container Facility	Steam Boiler	3.75E-01	658,173	3,692,039	26.90	410.00	0.03	2.30
Georgetown	GEO35	Praxair, Inc	Product Vaporizers	1.00E-02	658,694	3,692,939	32.80	400.70	0.03	0.67
Georgetown	GEO36	AGSC	EP5	4.88E-02	653,179	3,689,173	148.43	190.00	66.09	5.67
Georgetown	GEO37	AGSC	EP8	2.71E-02	653,167	3,689,161	148.43	325.00	73.46	4.33
Georgetown	GEO38	AGSC	EP9	2.71E-02	653,173	3,689,167	148.43	325.00	73.46	4.33
Georgetown	GEO39	AGSC	EP18	1.03E-01	653,283	3,689,277	65.62	165.00	69.29	7.00
Jasper	JAS01	SCE&G-Jasper Co. Generating Facility	Turbines 1-3	3.20E+02	488,357	3,580,065	190.00	278.00	72.60	18.00
Jasper	JAS02	Wasteco	ACI	6.30E-01	509,387	3,587,885	30.00	1,000.00	1.33	20.18
Lexington	LEX01	Voridian	HEAT1011	5.92E+01	498,930	3,746,940	120.10	401.00	24.51	3.94
Lexington	LEX02	Voridian	16M08 ID#6	-4.01E+01	498,864	3,746,962	74.80	750.00	18.30	3.00
Lexington	LEX03	Voridian	16M08 ID#7	-4.01E+01	498,864	3,746,962	74.80	400.70	11.60	3.00
Lexington	LEX04	Voridian	18K02-13	6.36E+01	498,727	3,746,520	120.10	400.00	23.50	3.28
Lexington	LEX05	Michelin Tire Corp	124_44	7.54E+01	473,400	3,755,000	120.00	280.00	46.80	1.22
Lexington	LEX06	SMI Steel SC	Baghouse #1 East Section	1.08E+01	495,162	3,757,793	85.00	230.00	9.52	29.86
Lexington	LEX07	SMI Steel SC	Baghouse #2 West Section	1.08E+01	495,140	3,757,784	85.00	230.00	9.52	29.86
Lexington	LEX08	SMI Steel SC	Roll Mill Reheat Furnace	3.44E+01	495,384	3,757,760	91.00	91.00	70.13	5.00
Lexington	*LEX09*	*SMI Steel SC*	*Melt Shop*	*2.18E-01*	*495,230*	*3,757,856*	*48.56*	*26.70*	*45.30*	
Lexington	LEX10	United Parcel Service - Air Hub	Generator	3.50E-02	489,962	3,754,514	13.85	922.70	1,136.00	0.50
Marion	MAR01	Cone Mills-Raytex Finishing	TR01B	9.00E-03	646,597	3,780,598	39.00	280.00	43.00	2.90
Marion	MAR02	Cone Mills-Raytex Finishing	TF03B	8.00E-03	646,597	3,780,598	40.50	300.00	46.77	2.33
Marion	MAR03	Cone Mills-Raytex Finishing	Boiler 1	-4.43E+01	646,597	3,780,598	35.50	384.00	25.00	2.00
Marion	MAR04	Cone Mills-Raytex Finishing	Boiler 2	2.24E+01	646,597	3,780,598	37.75	495.00	42.00	2.83
Marion	MAR05	Blumenthal Mills, Inc.	Boiler #2	2.51E+01	646,273	3,782,473	56.40	350.00	30.60	2.50
Marion	MAR06	Blumenthal Mills, Inc.	Tenter Frame #1	1.00E-02	646,349	3,782,473	27.80	300.00	20.00	3.08
Marlboro	MAL01	MOHAWK CARPETS-OAK RIVER MILL	Boiler 3	-1.63E+01	617,822	3,817,628	44.00	540.00	23.20	3.50
Marlboro	MAL02		Boiler 4	1.06E+01	617,745	3,818,066	50.00	416.00	33.50	2.00
Marlboro	MAL03		Boiler 5	1.06E+01	617,745	3,818,066	50.00	416.00	33.50	2.00
Marlboro	MAL04		Boiler 6	1.06E+01	617,745	3,818,066	50.00	416.00	33.50	2.00
Marlboro	MAL05	Willamette Industries	Recovery Boiler	2.17E+02	612,270	3,829,521	250.00	332.30	65.60	10.00
Marlboro	MAL06	Willamette Industries	Hog Fuel Boiler	4.95E+01	612,178	3,829,427	154.90	305.30	69.23	8.00
Marlboro	MAL07	Willamette Industries	Lime Kiln #1&#2	1.06E+01	612,330	3,829,392	142.10	434.90	101.00	4.00
Marlboro	MAL08	Willamette Industries	Smelt Dissolving Tank	4.90E+00	612,288	3,829,548	140.10	188.30	33.46	4.50
Marlboro	MAL09	Willamette Industries	NCG Incinerator	6.00E+00	612,225	3,829,468	51.84	167.00	56.10	1.51
Marlboro	MAL10	Willamette Industries	Package Boiler	5.00E-01	612,249	3,829,538	60.04	318.00	40.35	6.50
Marlboro	MAL11	Willamette Industries (ECCI)	Carbonator System	6.20E+00	612,381	3,829,413	54.13	154.00	7.71	2.99
Marlboro	MAL12	Willamette Industries (MDF)	TCO Control Device	1.03E-02	612,000	3,828,611	45.00	145.00	50.00	7.50
Marlboro	MAL13	Willamette Industries (MDF)	Dryer RTO	1.12E-01	613,135	3,829,089	44.90	145.00	50.00	7.50
Marlboro	MAL14	Willamette Industries (MDF)	Press RTO	1.00E-02	613,120	3,829,102	45.00	145.00	39.40	8.70
Marlboro	MAL15	Willamette Industries (MDF)	Hot Oil System	5.00E-01	613,137	3,829,154	44.90	199.00	45.00	1.30
Orangeburg	ORA01	Albemarle Corp	701 HE-950-1	7.18E-01	511,188	3,702,794	26.00	514.00	0.03	1.00
Orangeburg	ORA02	Albemarle Corp	701 HE-950-2	7.08E-01	511,179	3,702,794	27.00	450.00	0.03	1.50
Orangeburg	ORA03	Albemarle Corp	DR-3 Diesel Engine 11	2.60E-01	511,038	3,702,544	11.00	1,009.00	137.00	0.67
Orangeburg	ORA04	Albemarle Corp	HCN Diesel Engine 12	1.25E-01	511,098	3,702,453	12.00	939.00	178.00	0.50
Orangeburg	ORA05	Albemarle Corp	HCN Flare	4.20E-03	511,193	3,702,464	100.00	1,000.00	10.57	2.00
Orangeburg	ORA06	Holnam, Inc.	(81) #1 Kiln ESP	-4.78E+02	552,975	3,682,388	149.84	307.00	30.05	10.99
Orangeburg	ORA07	Holnam, Inc.	(82) #2 Kiln ESP	-1.49E+03	552,988	3,682,467	160.00	354.00	49.87	12.24
Orangeburg	ORA08	Holnam, Inc.	(94) Preheater/Precalciner Kiln	8.54E+02	553,206	3,682,052	359.25	244.00	51.80	20.00
Orangeburg	ORA09	Holnam, Inc.	(95) Coal Mill Vent	6.19E+01	553,170	3,682,082	137.80	185.00	77.36	4.27
Orangeburg	ORA10	SCE&G-Cope	Unit 1 Boiler	1.00E+03	497,200	3,691,400	524.80	150.71	49.00	23.00
Orangeburg	ORA11	Carolina Pole, Inc	Kiln Boiler	5.22E+01	559,488	3,692,767	51.00	400.00	52.00	2.00
Orangeburg	ORA12	Orangeburg Dept. of Public Utilities	Generator 1&2	5.40E+01	508,072	3,711,611	22.00	800.00	89.10	3.50
Orangeburg	ORA13	City of Orangeburg	Hot Oil Burner Exhaust	8.00E-03	513,426	3,700,069	33.50	650.00	14.99	2.00
Orangeburg	ORA14	City of Orangeburg	350 kW Generator	9.70E-01	513,426	3,700,069	19.00	1,219.70	475.43	0.54
Orangeburg	ORA15	City of Orangeburg	500 kW Generator	2.70E-01	513,426	3,700,069	19.00	1,219.70	475.43	0.54
Orangeburg	ORA16	City of Orangeburg	900 kW Generator	4.90E-01	513,426	3,700,069	17.88	865.10	920.14	0.54
Orangeburg	ORA17	Pennington Crossarm Co.	Boiler	4.26E+00	552,475	3,688,714	30.00	455.00	0.03	1.30
Richland	RIC01	Carolina Ceramics, Inc.	Kilns 3 & 4	2.67E+01	509,444	3,774,663	65.94	350.00	43.31	3.28
Richland	RIC02	Carolina Ceramics, Inc.	Brick Dryers for Kilns 3 & 4	2.40E-03	509,444	3,774,663	35.10	98.00	32.81	3.94
Richland	RIC03	Fort Jackson	B1699 - CEP#3 Boilers #1,2&3	2.65E+01	505,324	3,761,356	55.00	445.00	0.03	3.00
Richland	RIC04	Fort Jackson	B1699 - CEP#3 Old Boilers #1,2,&3	-1.80E+02	505,324	3,761,356	55.00	445.00	0.03	3.00
Richland	RIC05	Fort Jackson	B1701 - Boiler & Diesel Engine	7.57E-02	505,535	3,761,593	15.00	350.00	0.03	0.83
Richland	RIC06	Fort Jackson	B2100 - Boiler	6.00E-03	503,836	3,762,104	44.00	200.00	0.03	1.30
Richland	RIC07	Fort Jackson	B2288 - CEP#1 Boilers #1,2,&3	5.02E+00	504,405	3,762,491	55.00	350.00	0.03	3.70
Richland	RIC08	Fort Jackson	B2288 - CEP#1 Old Boilers #1,2&3	-2.71E+02	504,405	3,762,491	55.00	350.00	0.03	3.70
Richland	RIC09	Fort Jackson	B4333 - CEP#2 Boilers #1-#5	6.58E+01	505,253	3,763,632	55.00	300.00	0.03	3.72
Richland	RIC10	Fort Jackson	B4333 - CEP#2 Old Boilers #1-#5	-3.92E+02	505,253	3,763,632	55.00	350.00	0.03	3.72
Richland	RIC11	Fort Jackson	CEP3CHL - CEP #3 Chiller	1.00E-03	505,324	3,761,356	20.00	300.00	0.03	9.56
Richland	RIC12	Fort Jackson	H032E - Boiler	3.30E-02	506,931	3,764,149	46.50	350.00	0.03	3.00
Richland	RIC13	Cardinal Stabilizers	Boiler 1 800hp	1.69E+01	501,571	3,757,465	30.00	538.00	41.70	2.00
Richland	RIC14	Cardinal Stabilizers	Boiler 2 300hp	5.04E+00	501,571	3,757,465	25.00	325.00	20.50	1.50
Richland	RIC15	Cardinal Stabilizers	Boiler 4 800hp	1.69E+01	501,571	3,757,465	30.00	538.00	41.70	2.00
Richland	RIC16	Cardinal Stabilizers	Boiler 3 400hp	-6.79E+00	501,571	3,757,465	25.00	325.00	20.50	1.50
Richland	RIC17	Palmetto Baptist Medical Center	Boiler #1	7.54E+00	496,930	3,762,909	99.50	400.00	3.17	9.00
Richland	RIC18	Palmetto Baptist Medical Center	Boiler #3	7.54E+00	496,930	3,762,909	99.50	400.00	3.17	9.00
Richland	RIC19	Palmetto Baptist Medical Center	Boiler #4	9.00E-03	496,930	3,762,909	127.00	400.00	0.03	1.66
Richland	RIC20	Palmetto Baptist Medical Center	Old Boiler #1	-1.06E+01	496,930	3,762,909	140.00	475.00	12.02	3.66
Richland	RIC21	Palmetto Baptist Medical Center	Old Boiler #3	-1.06E+01	496,930	3,762,909	140.00	475.00	12.02	3.66
Richland	RIC22	International Paper - Eastover (formerly Union	No. 1 Smelt Dissolving Tank	3.50E+00	533,376	3,749,431	249.00	169.00	21.33	4.60
Richland	RIC23	International Paper - Eastover (formerly Union	No. 2 Smelt Dissolving Tank	7.80E+00	533,394	3,749,465	249.00	172.00	27.56	5.90
Richland	RIC24	International Paper - Eastover (formerly Union	No. 2 NCG Incin/No. 2 RecFurn	1.12E+03	533,363	3,749,523	463.00	370.00	50.85	14.11
Richland	RIC25	International Paper - Eastover (formerly Union	No. 1 RecFurn/No. 1 Power Boiler	1.38E+03	533,311	3,749,506	282.50	367.00	56.43	13.45
Richland	RIC26	International Paper - Eastover (formerly Union	No. 2 Power Boiler	9.64E+02	533,259	3,749,490	463.00	377.00	68.24	9.50
Richland	RIC27	International Paper - Eastover (formerly Union	No. 1 Lime Kiln	9.20E+00	533,484	3,749,711	177.00	134.00	35.00	5.90
Richland	RIC28	International Paper - Eastover (formerly Union	No. 2 Lime Kiln	1.31E+01	533,486	3,749,770	177.00	473.00	70.00	5.90
Richland	RIC29	Richland Memorial Hospital	Boiler 2-600HP	1.28E+01	497,000	3,765,123	30.00	395.00	0.03	4.00
Richland	RIC30	Richland Memorial Hospital	Boiler 3-800HP	1.70E+01	497,000	3,765,123	35.50	395.00	19.73	2.00
Richland	RIC31	Richland Memorial Hospital	Removed boiler-1250HP	-1.37E+02	497,000	3,765,123	36.00	410.00	7.73	4.00
Richland	RIC32	SC Dept of Corrections	Boiler #1&2	-1.19E+02	489,224	3,767,966	20.00	450.00	35.32	2.41
Richland	RIC33	Springs Industries - Olympia	Boiler #1&2	4.62E+01	496,044	3,760,000	175.00	360.00	1.90	8.00
Richland	RIC34	USC Central Energy Facilities	West Boiler #1	1.70E+01	497,229	3,761,192	44.00	475.00	37.63	2.50
Richland	RIC35	USC Central Energy Facilities	West Boiler #2	2.76E+01	497,229	3,761,192	46.00	475.00	14.70	4.00
Richland	RIC36	USC Central Energy Facilities	East Boiler #1	1.72E+01	497,768	3,761,777	50.00	374.00	14.00	4.00
Richland	RIC37	USC Central Energy Facilities	East Boiler #2	1.72E+01	497,768	3,761,777	50.00	374.00	14.00	4.00
Richland	RIC38	USC Central Energy Facilities	East Boiler #3	1.72E+01	497,768	3,761,777	50.00	374.00	35.90	2.50
Richland	RIC39	USC Central Energy Facilities	BLR13_14 - Arnold School of Public	1.20E-02	497,229	3,761,192	60.00	300.00	0.03	1.70
Richland	RIC40	USC Central Energy Facilities	BLR21_22 - Colonial Center	8.00E-03	497,229	3,761,192	56.00	300.00	0.03	3.00
Richland	RIC41	USC Central Energy Facilities	Biomass Gasifier Boiler System	2.70E+00	496,408	3,760,976	70.00	295.00	56.67	6.00

Table A-1. Regional Inventory Sources

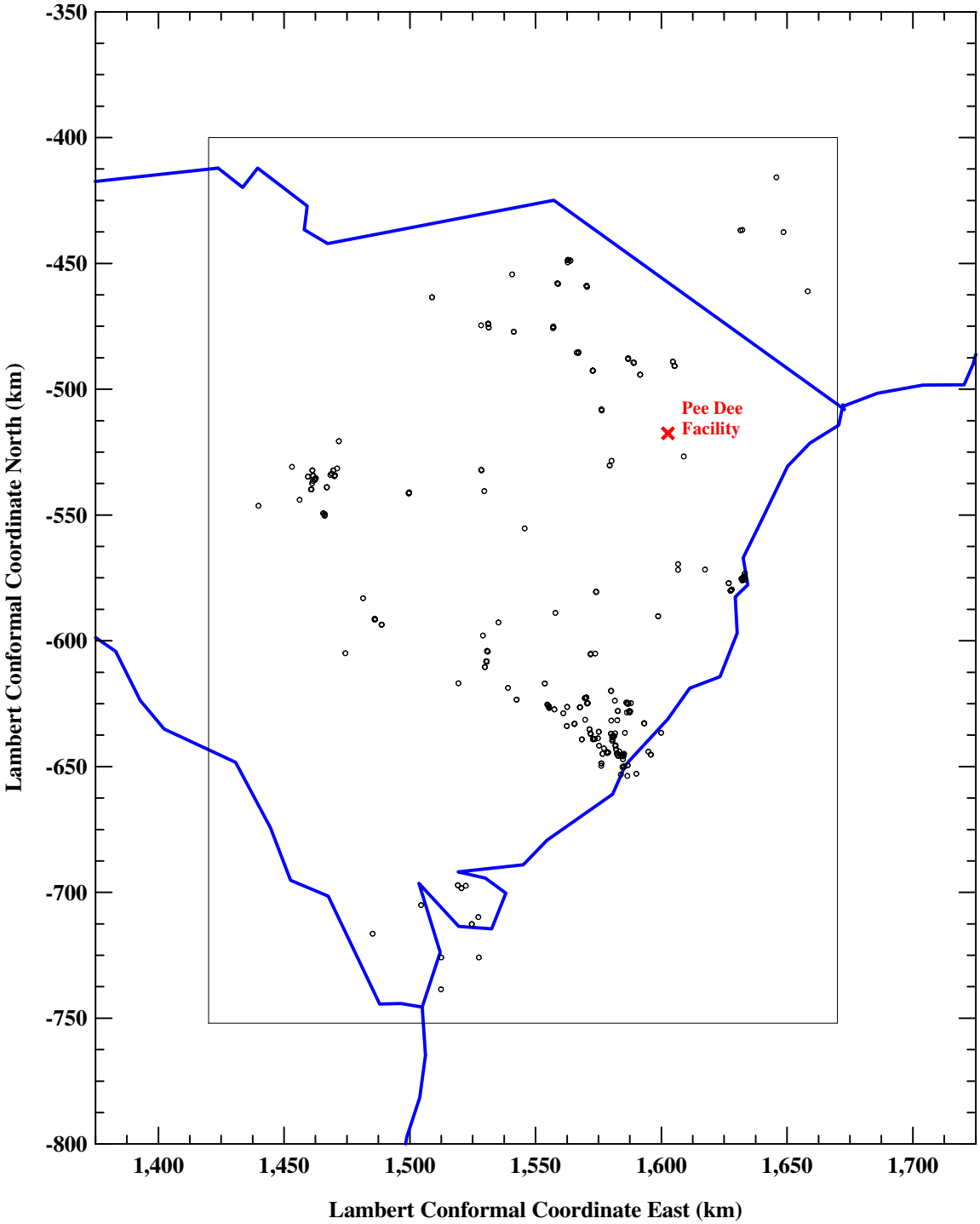
County	ID	Company Name	Stack Details	SO_2 Emissions (lb/hr)	UTM East (m)	UTM North (m)	Height (ft)	Temp °F	Modeled Velocity (ft/s)	Diameter (ft)
Richland	RIC42	USC Central Energy Facilities	Old East Boiler #1	-2.15E+01	497,768	3,761,777	50.00	374.00	14.00	4.00
Richland	RIC43	USC Central Energy Facilities	Old East Boiler #2	-2.15E+01	497,768	3,761,777	50.00	374.00	14.00	4.00
Richland	RIC44	USC Central Energy Facilities	Old East Boiler #3	-2.76E+01	497,768	3,761,777	50.00	374.00	35.90	2.50
Richland	RIC45	USC Central Energy Facilities	Old West Boiler #1	-2.76E+01	497,229	3,761,192	44.00	475.00	37.63	2.50
Richland	RIC46	Office of General Services energy fac.	Old Boiler No. 1	-7.51E+00	494,870	3,762,948	45.50	325.00	0.03	3.00
Richland	RIC47	Office of General Services energy fac.	Old Boiler No. 2	-7.51E+00	494,870	3,762,948	45.50	325.00	0.03	3.00
Richland	RIC48	Office of General Services energy fac.	New Boiler No. 1	1.70E+01	494,870	3,762,950	45.00	390.00	55.50	2.00
Sumter	SUM01	Santee Print Works	Stack 130 Bleach Range	1.40E-02	563,395	3,753,426	23.20	350.00	0.03	43.60
Sumter	SUM02	Santee Print Works	Stack 44 Boiler 4	3.47E+02	563,395	3,753,426	90.00	450.00	30.00	5.00
Sumter	SUM03	Santee Print Works	Stack 106 Finish A	9.63E-03	563,395	3,753,426	45.00	350.00	15.10	2.00
Sumter	SUM04	Santee Print Works	Stack 108 Finish B	1.28E-02	563,395	3,753,426	36.70	350.00	0.03	30.87
Sumter	SUM05	Santee Print Works	Stack 53 SCR PRT	2.00E-02	563,395	3,753,426	34.70	350.00	0.03	64.00
Sumter	SUM06	Santee Print Works	Stack 74 ASD	6.00E-03	563,395	3,753,426	37.20	350.00	0.03	50.60
Sumter	SUM07	Santee Print Works	Stack 79 Tint/Dye	7.00E-03	563,395	3,753,426	35.50	350.00	0.03	43.40
Sumter	SUM08	Santee Print Works	Stack 69 Space Heater	5.00E-03	563,395	3,753,426	36.20	350.00	0.03	27.90
Sumter	SUM09	City of Sumter	Stack 1	1.00E-02	563,169	3,745,078	65.00	130.00	49.00	1.25
Florence	FLO28	Dupont-Florence	Boiler #3	3.10E+02	630,885	3,784,747	125.00	350.00	26.80	5.00
Florence	FLO29	Dupont-Florence	Dow Vaporizer 1	7.40E+00	630,830	3,784,790	125.00	500.00	15.20	3.44
Florence	FLO30	Dupont-Florence	Dow Vaporizer 2	7.40E+00	630,835	3,784,795	125.00	500.00	15.20	3.44
Florence	FLO31	Dupont-Florence	Dow Vaporizer 3	3.60E+01	630,848	3,784,778	125.00	500.00	7.61	3.44
Florence	FLO32	Dupont-Florence	Dow Vaporizer 4	3.60E+01	630,855	3,784,771	125.00	500.00	7.61	3.44
Florence	FLO33	Dupont-Florence	Dow Vaporizer 5	3.60E+01	630,863	3,784,764	125.00	500.00	7.61	3.44
Florence	FLO34	Dupont-Florence	Old Oil Boiler	-2.24E+02	630,841	3,784,804	125.00	350.00	26.60	5.00
Florence	FLO35	Dupont-Florence	Vaporizer 1&2 (pre-mSBD)	-5.73E+01	630,830	3,784,790	125.00	500.00	15.20	3.44
Florence	FLO36	Dupont-Florence	Vaporizer 3 (pre-mSBD)	-2.86E+01	630,848	3,784,778	125.00	500.00	19.00	3.44
Florence	FLO37	Dupont-Florence	Vaporizer 4 (pre-mSBD)	-2.86E+01	630,855	3,784,771	125.00	500.00	19.00	3.44
Florence	FLO38	Dupont-Florence	Package Boiler #1	3.18E+01	630,896	3,784,768	55.00	350.00	55.00	3.33
Florence	FLO39	Dupont-Florence	Package Boiler #2	3.18E+01	630,896	3,784,768	55.00	350.00	55.00	3.33
Bladen	BLA01	Browns of Carolina		2.87E+01	699,015	699,015	23.00	300.00	34.50	34.50
Bladen	BLA02	Carolina Food Processors		6.63E+01	700,119	700,119	60.00	364.00	78.20	78.20
Robeson	ROB01	Cogentrix of NC		6.46E+02	682,944	682,944	150.00	323.00	5.00	5.00
Robeson	ROB02	West Point Pepperell		8.65E+01	682,162	682,162	45.00	143.00	0.03	0.03

1. Volume and Area sources are listed in Italics. The parameters listed correspond to the appropriate volume and area source inputs.
2. Florence county sources FLO28 - FLO39 are included in the North Carolina model runs.

APPENDIX B

SUPPORTING FIGURES

FIGURE B-1. Regional Inventory

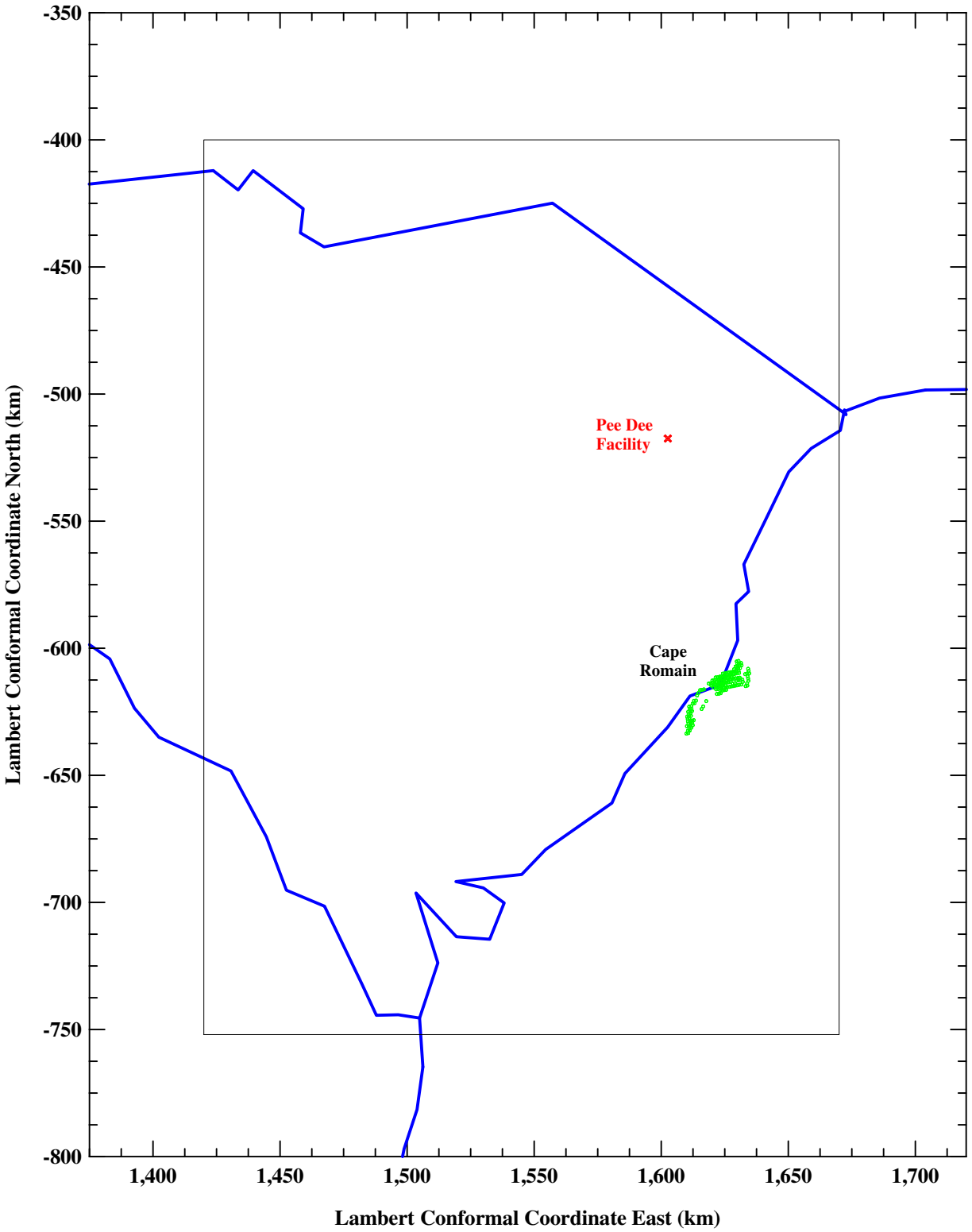


Edge Markings in Lambert Conformal Coordinates
LCC Origin: 40.0N 97.0 W

Trinity Consultants

Santee Cooper
051101.0107
Figure B-1 Regional Inventory.srf

FIGURE B-2. Domain and Receptors

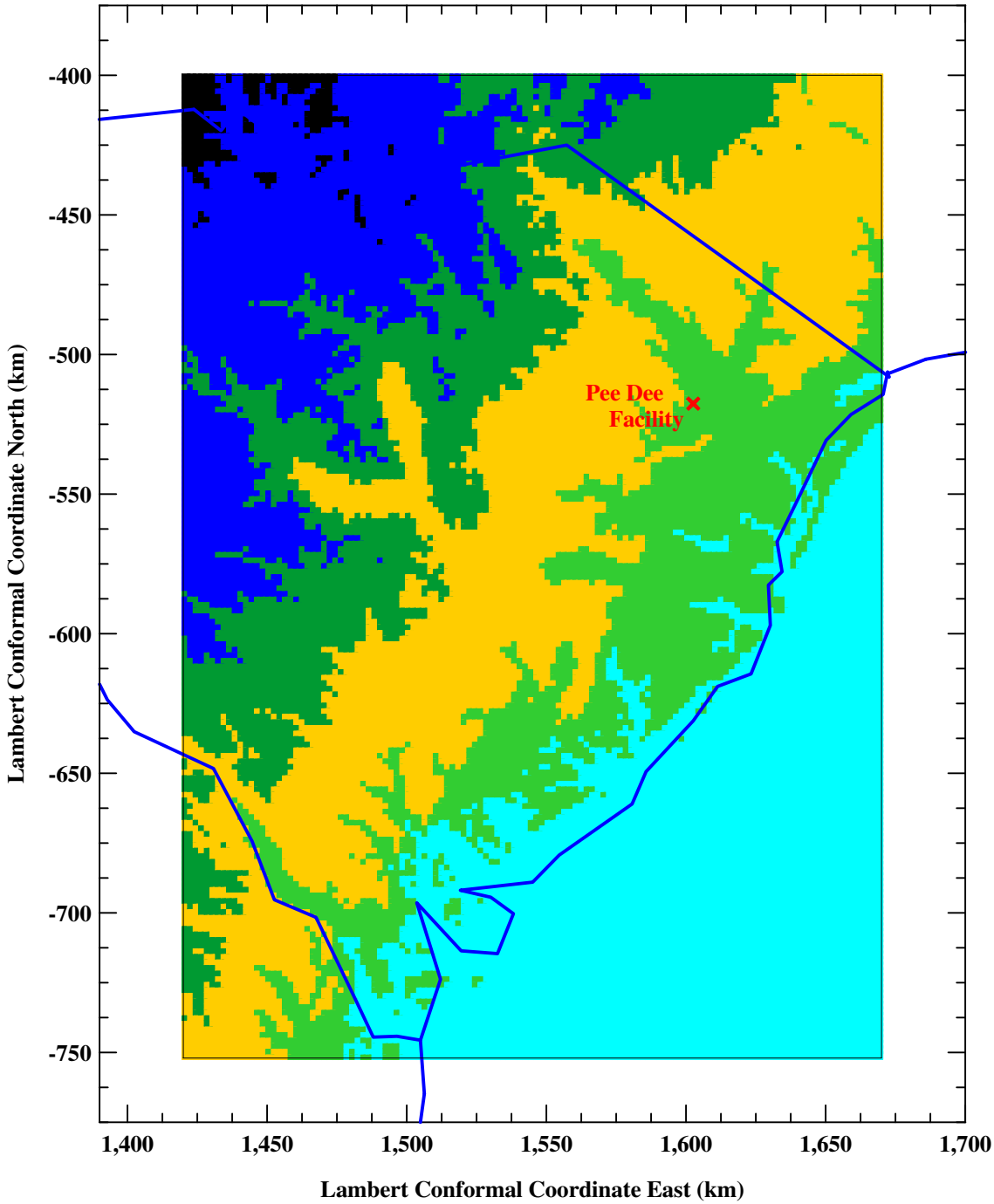


Edge Markings in Lambert Conformal Coordinates
LCC Origin: 40.0N 97.0 W

Trinity Consultants

Santee Cooper
051101.0107
Figure B-2 Domain and Receptors.srf

FIGURE B-3. Terrain



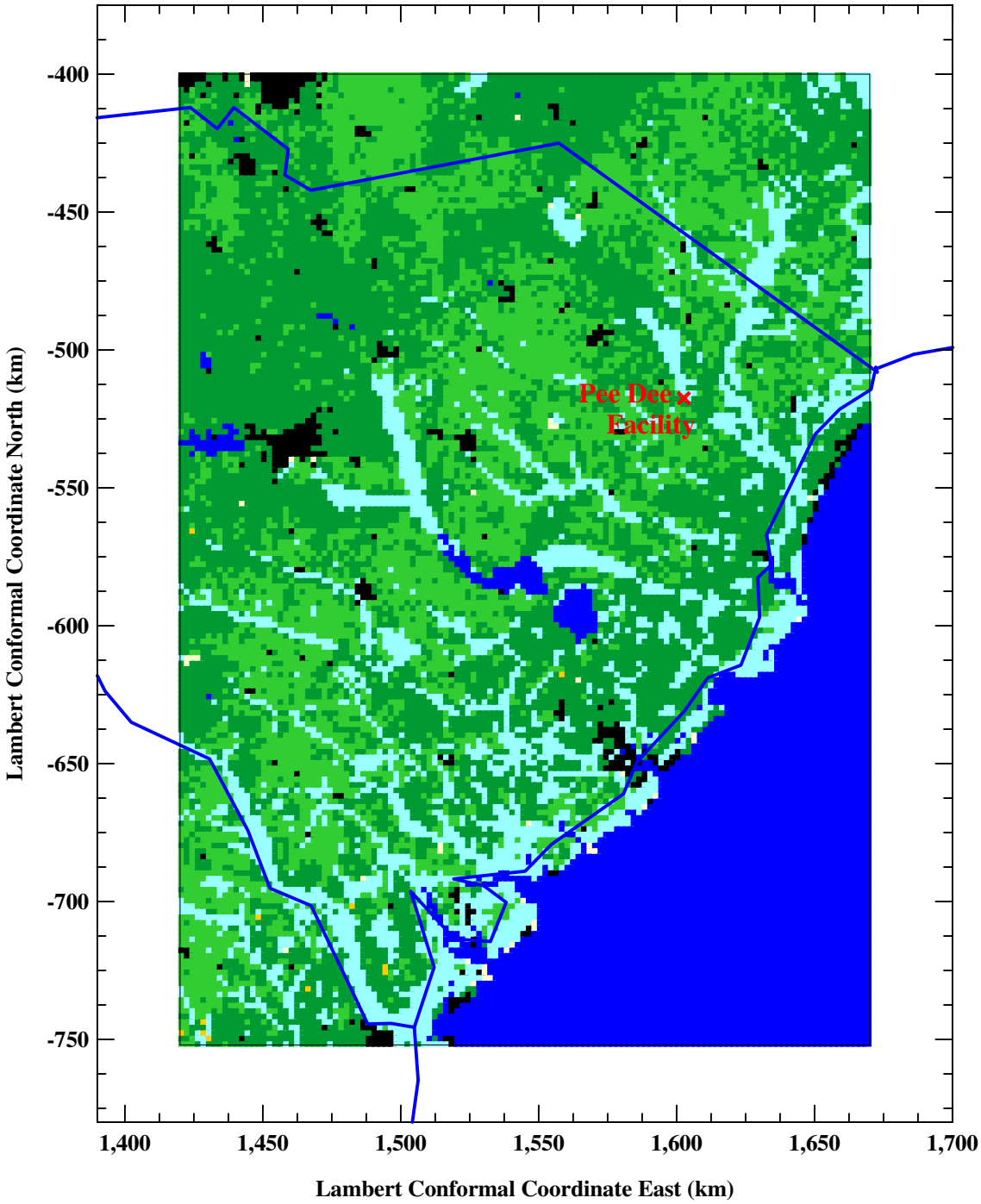
Edge Markings in Lambert Conformal Coordinates
LCC Origin: 40.0N 97.0 W

< 5 m
5 - 20 m
20 - 50 m
50 - 100 m
100 - 200 m
> 200 m

Trinity Consultants

Santee Cooper
051101.0107
Figure B-3 Terrain.srf

FIGURE B-4. Landuse



Edge Markings in Lambert Conformal Coordinates
LCC Origin: 40.0N 97.0 W

- Urban
- Agricultural
- Rangeland
- Forest
- Water
- Wetland
- Barren Land

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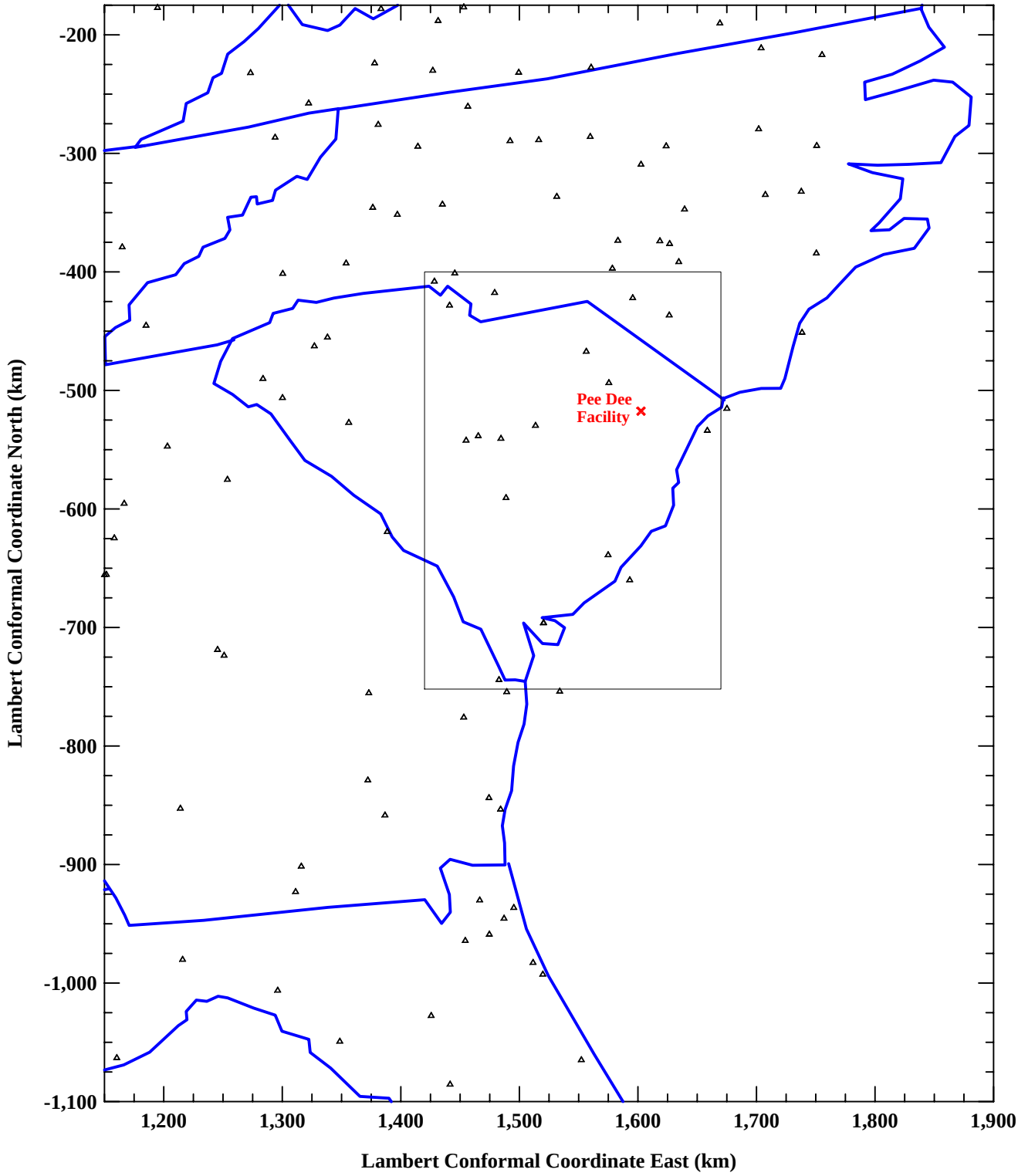
Figure B-4 Landuse.srf

FIGURE B-5. Meteorological Surface Stations



Edge Markings in Lambert Conformal Coordinates
LCC Origin: 40.0N 97.0 W

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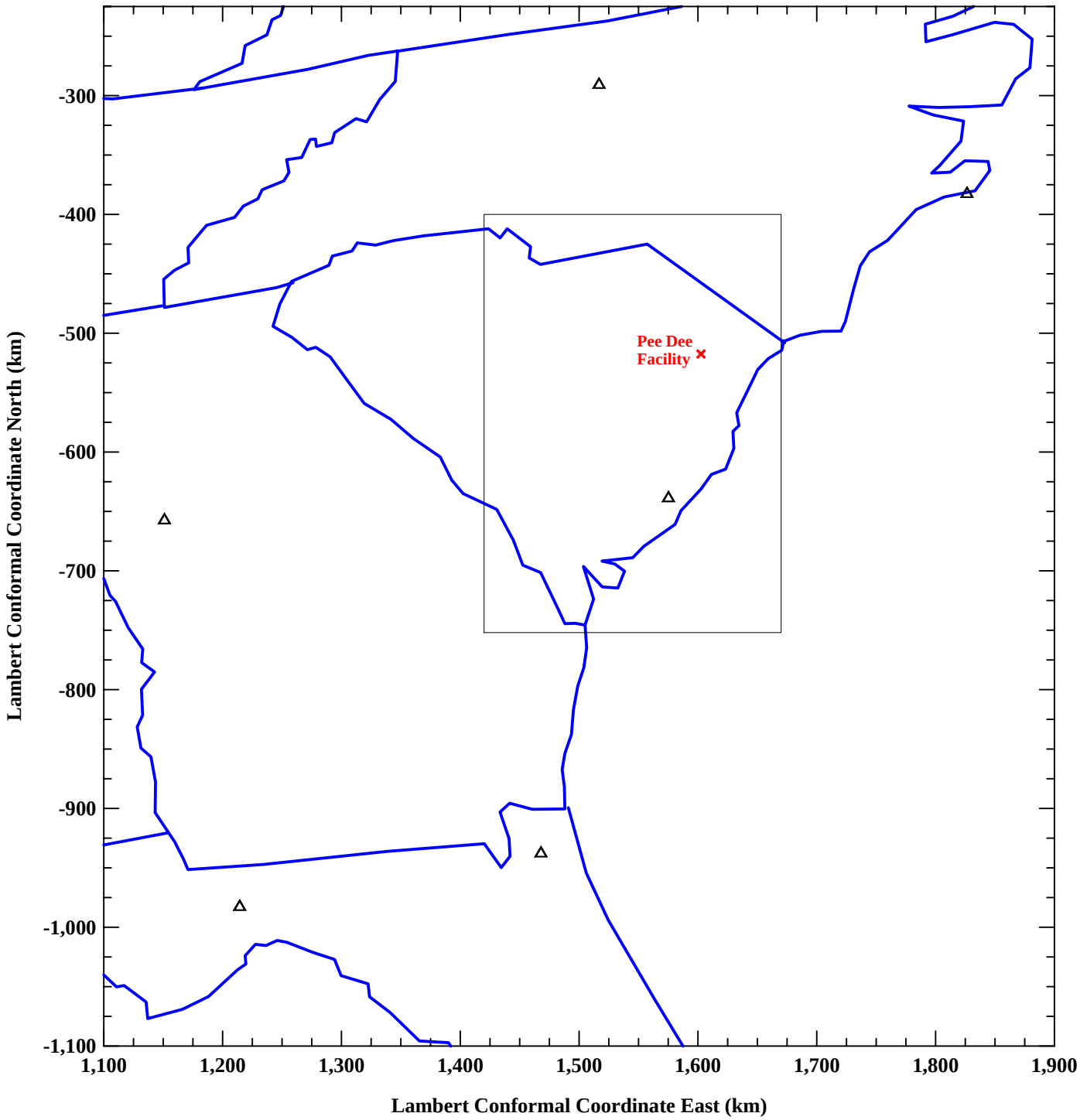
Figure B-5 Met Sfc Stations.srf

FIGURE B-6. Meteorological Upper Air Stations



Edge Markings in Lambert Conformal Coordinates
LCC Origin: 40.0N 97.0 W

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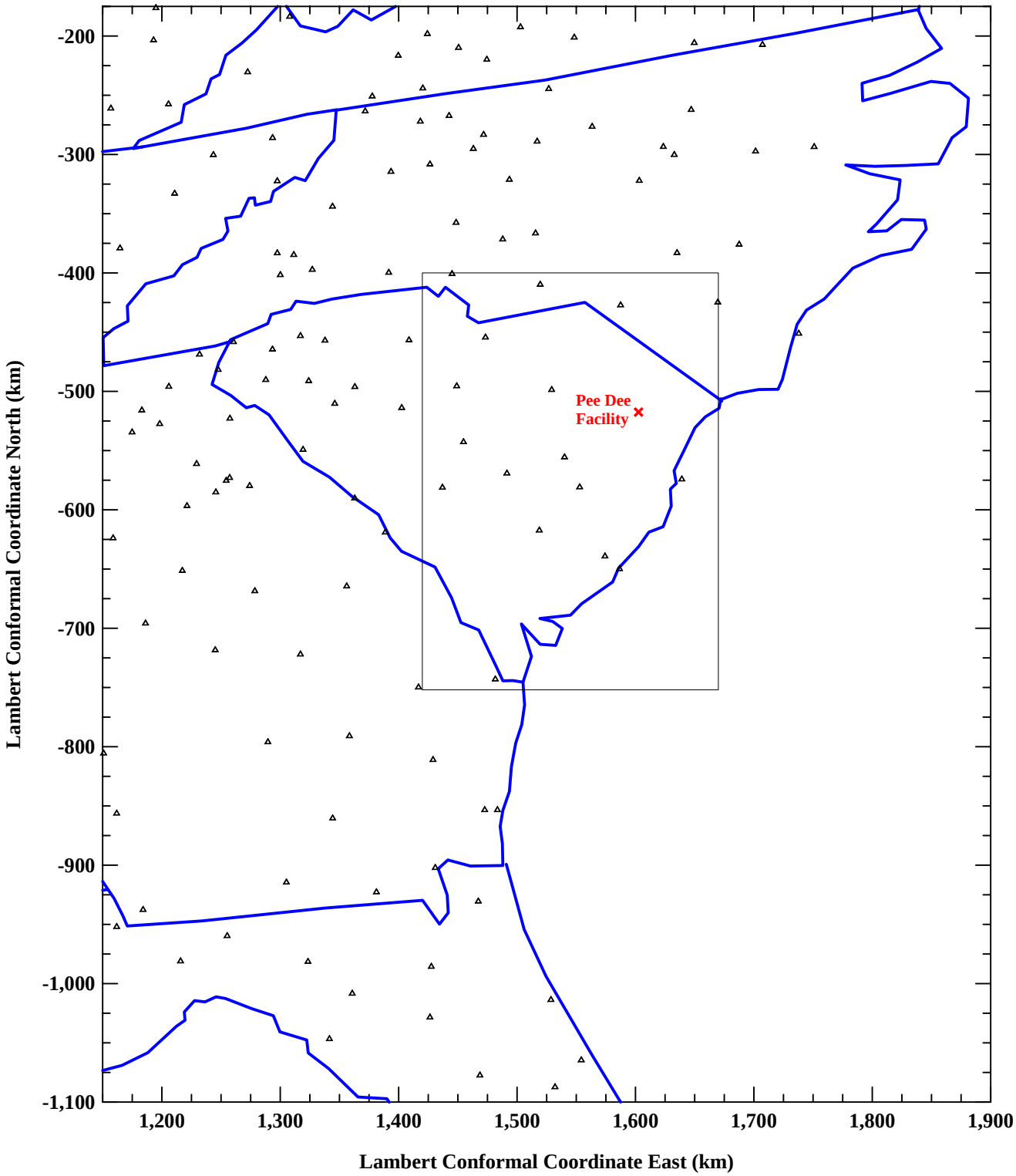
Figure B-6 Met UA Stations.srf

FIGURE B-7. Precipitation Stations



Edge Markings in Lambert Conformal Coordinates
LCC Origin: 40.0N 97.0 W

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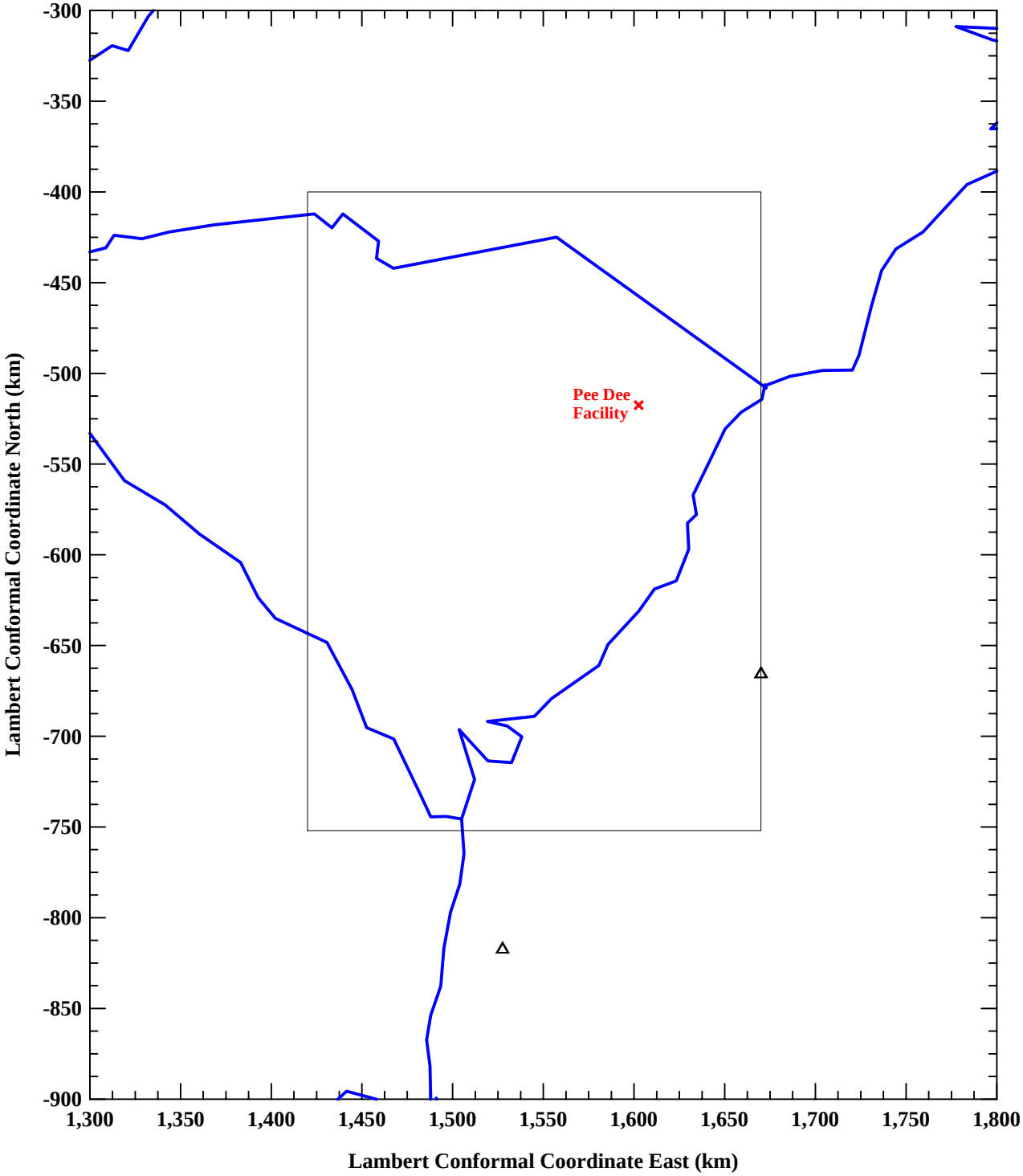
Figure B-7 Precip Stations.srf

FIGURE B-8. Overwater Stations



Edge Markings in Lambert Conformal Coordinates
LCC Origin: 40.0N 97.0 W

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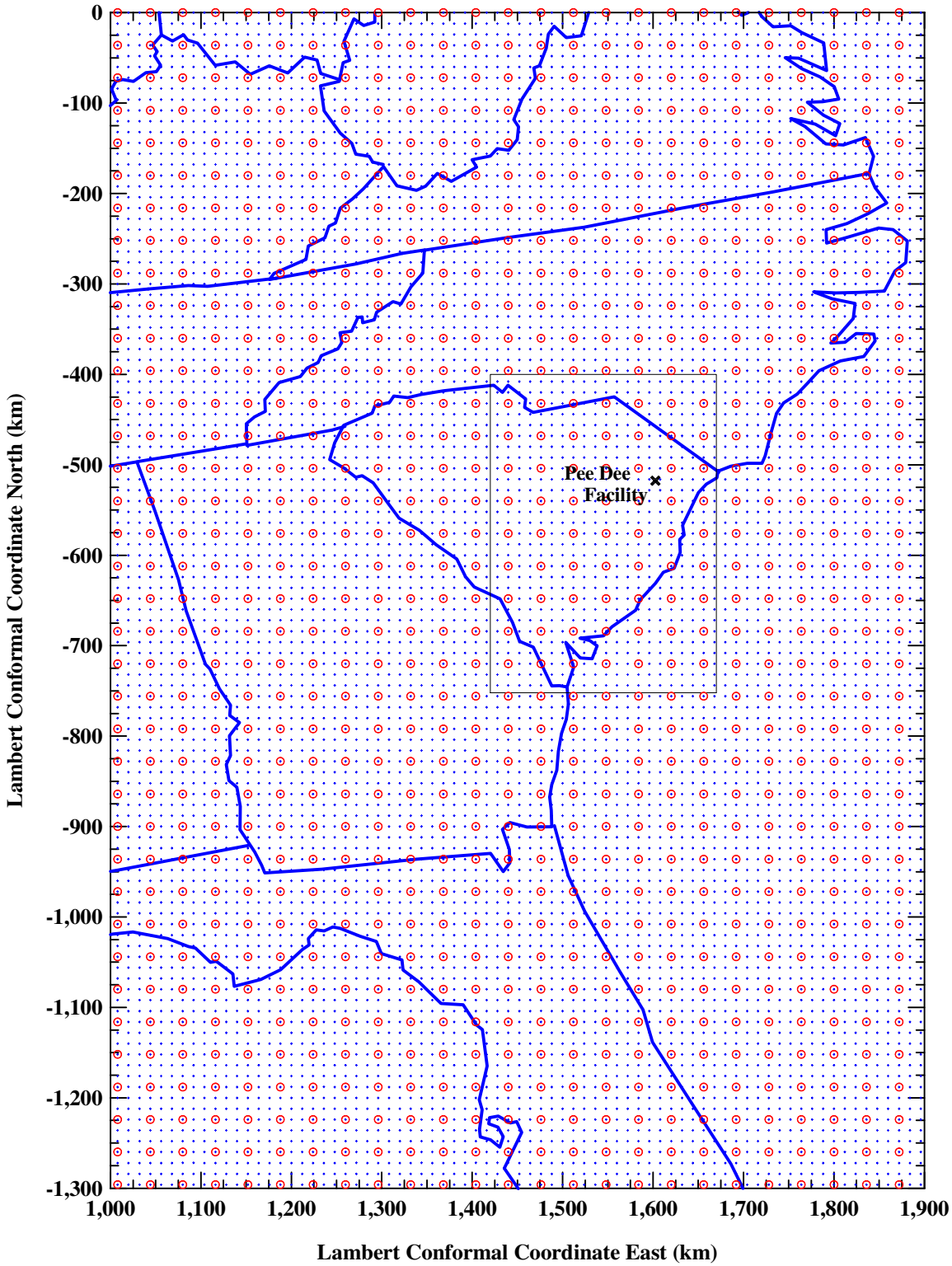
Figure B-8 Overwater Stations.srf

FIGURE B-9. MM Data Points



Edge Markings in Lambert Conformal Coordinates
LCC Origin: 40.0N 97.0 W

○ 2003 MM Data
+ 2001 and 2002 MM Data

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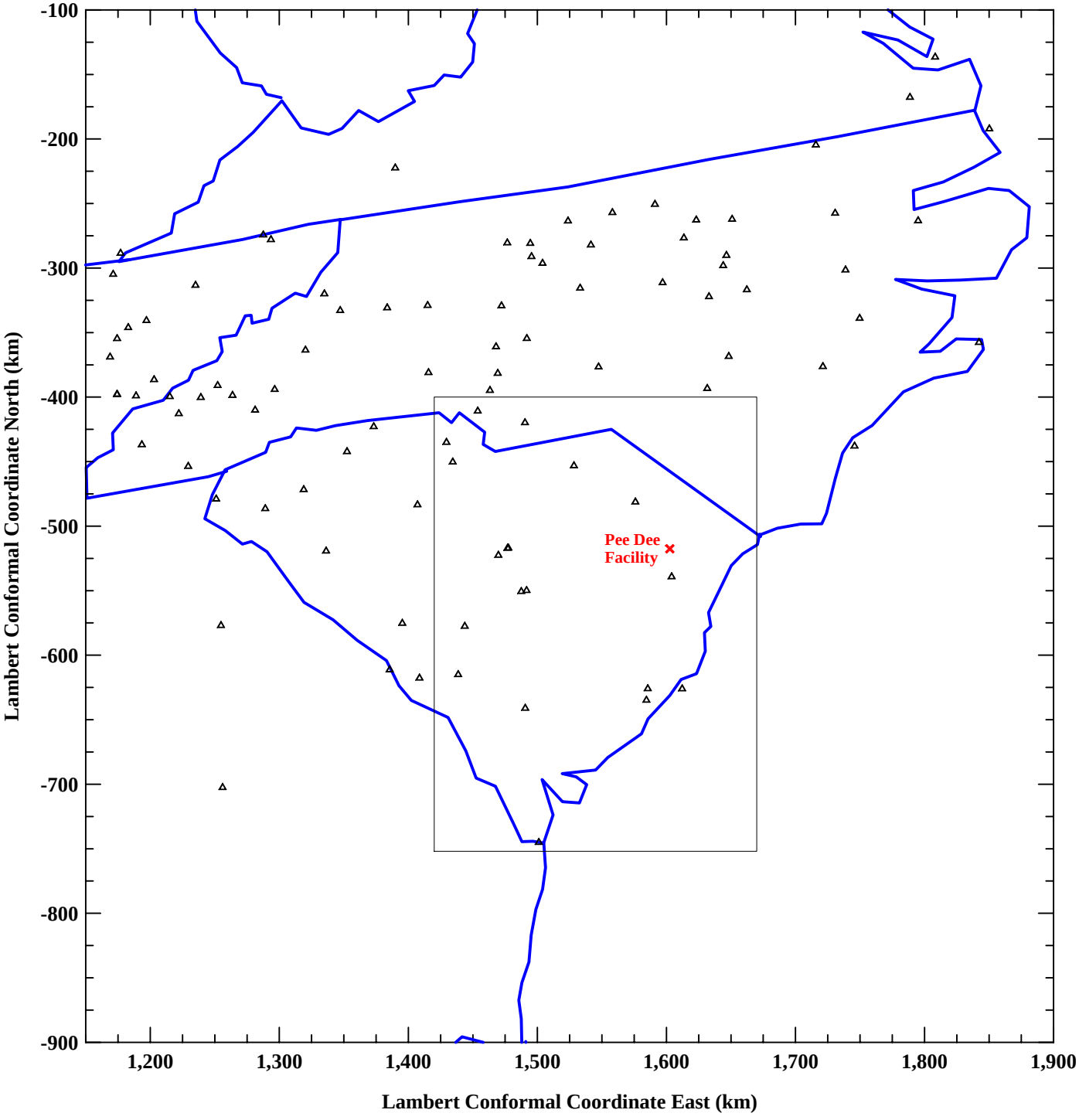
Figure B-9 MM Data Points.srf

FIGURE B-10. Ozone Stations



Edge Markings in Lambert Conformal Coordinates
LCC Origin: 40.0N 97.0 W

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Figure B-10 Ozone Stations.srf