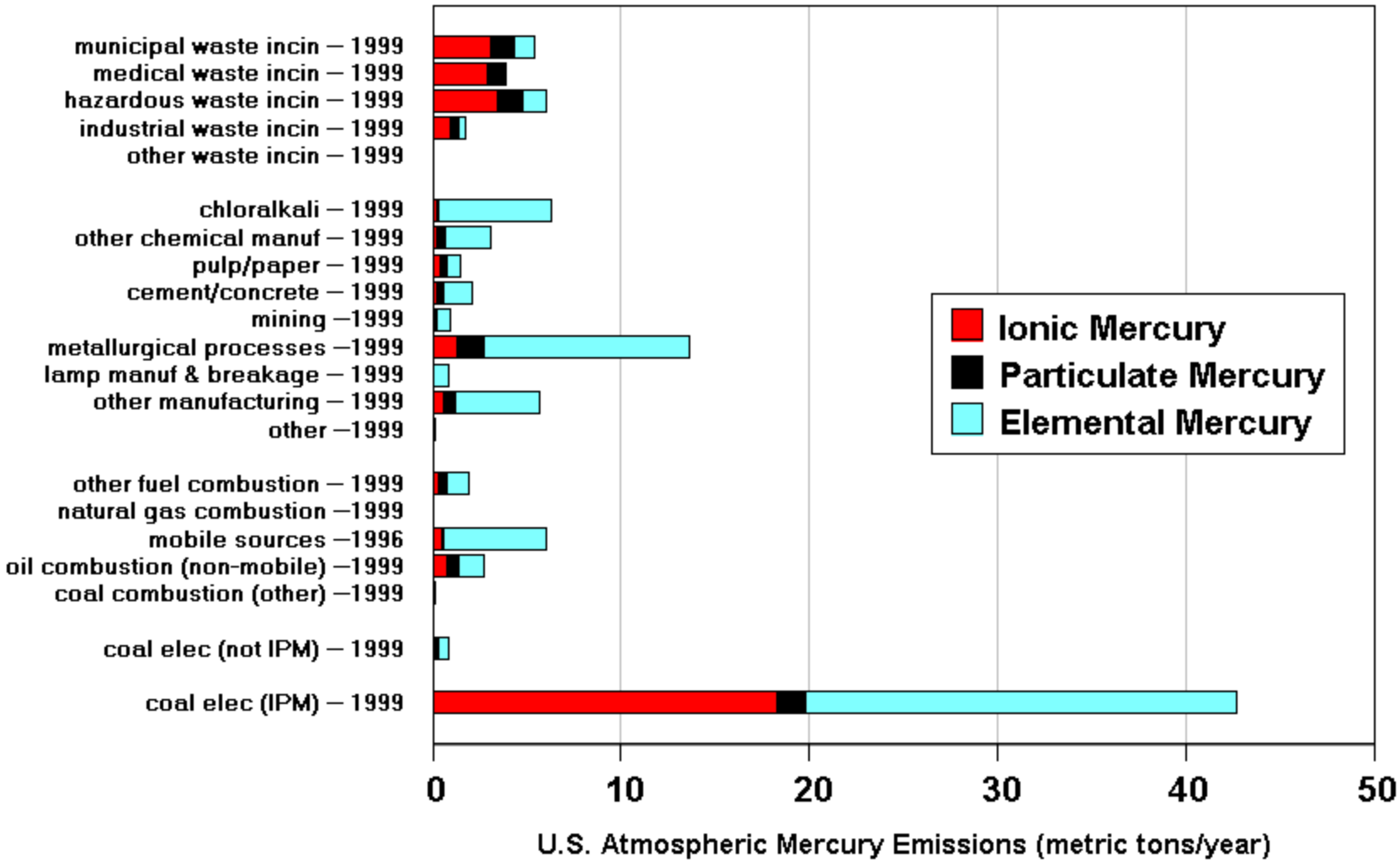
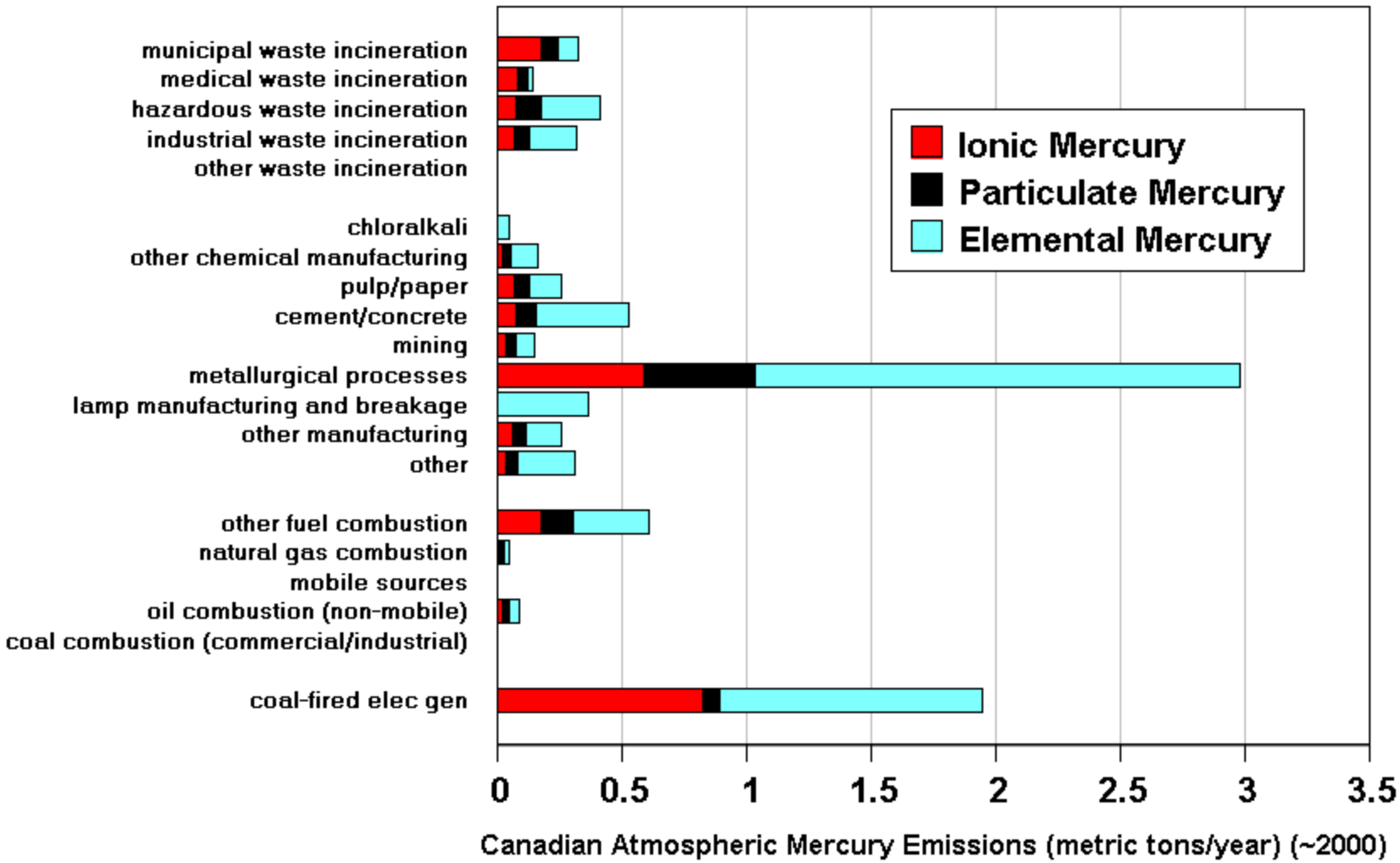
Estimated 1999 U.S. Atmospheric Anthropogenic Mercury Emissions



Estimated 2000 Canadian Atmospheric Anthropogenic Mercury Emissions

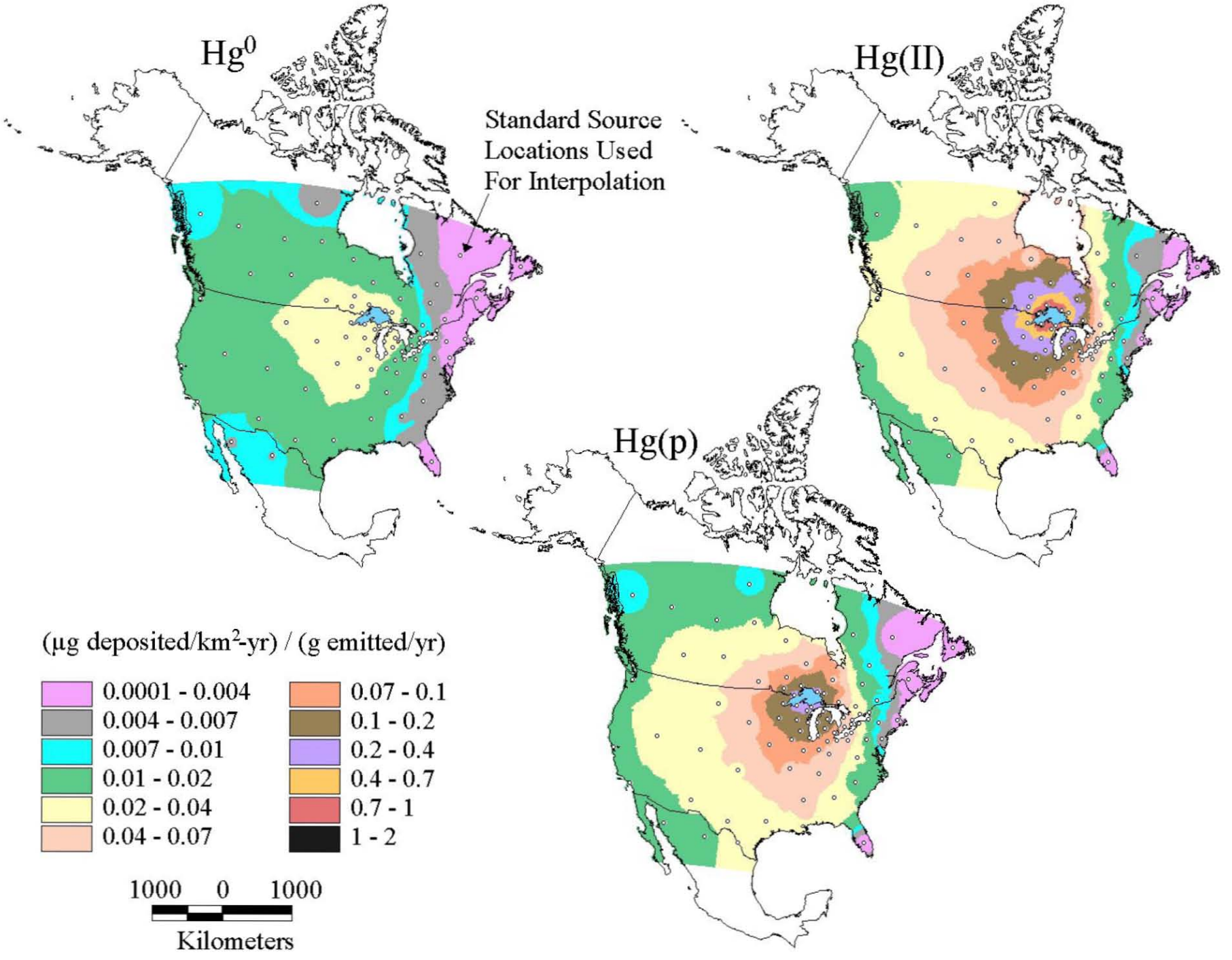


Very important to know how much of each form of mercury

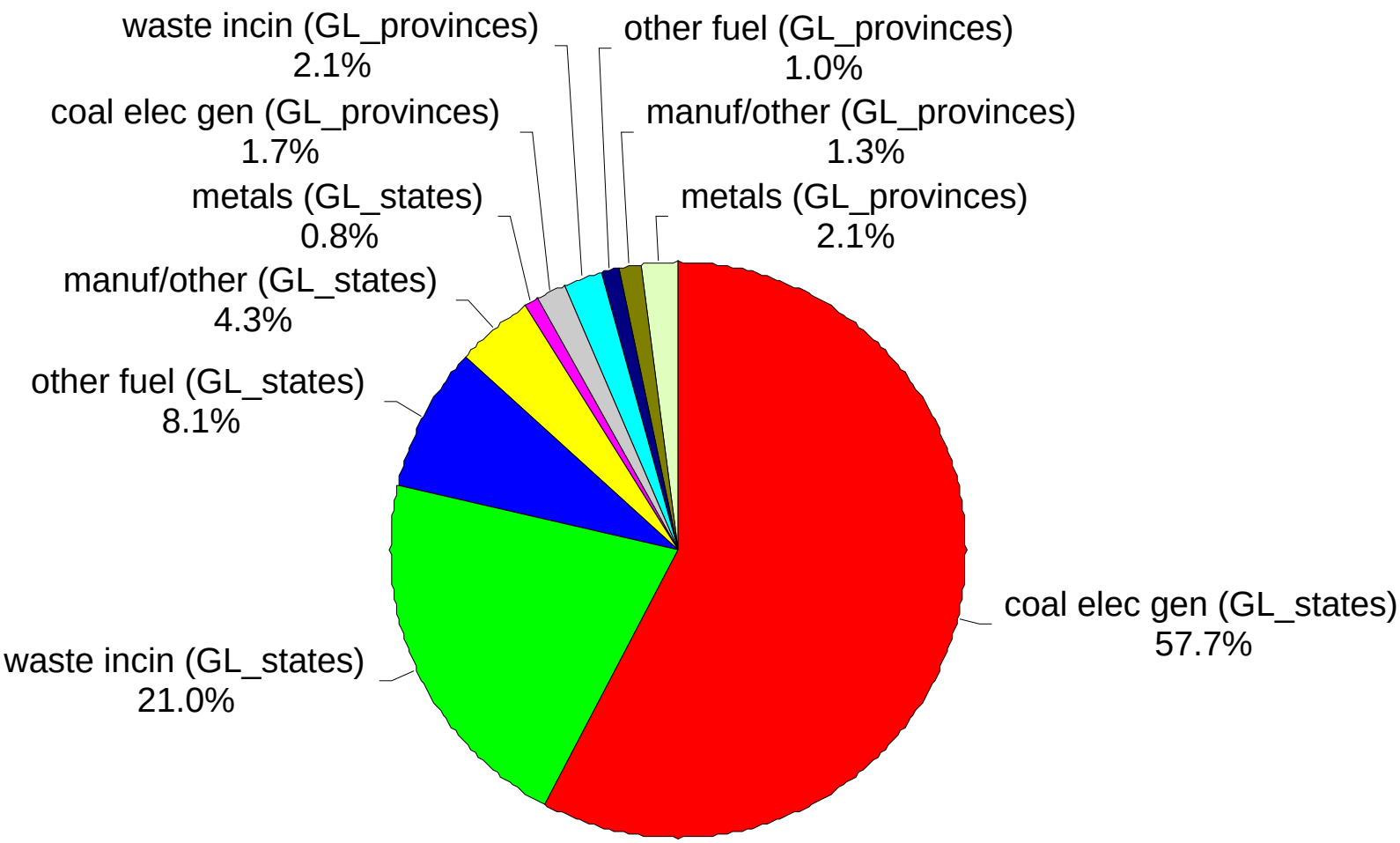
-- Hg(II), Hg(p), and Hg(0) --

is emitted from each source…

(this is usually very uncertain)


Hg0
Hg(II)
Hg(p)
Standard Source
Locations Used
For Interpolation
(µg deposited/km2-yr) / (g emitted/yr)
0.0001 - 0.004
0.004 - 0.007
0.007 - 0.01
0.01 - 0.02
0.02 - 0.04
0.04 - 0.07
0.07 - 0.1
0.1 - 0.2
0.2 - 0.4
0.4 - 0.7
0.7 - 1
1 - 2
1000 0 1000
Kilometers

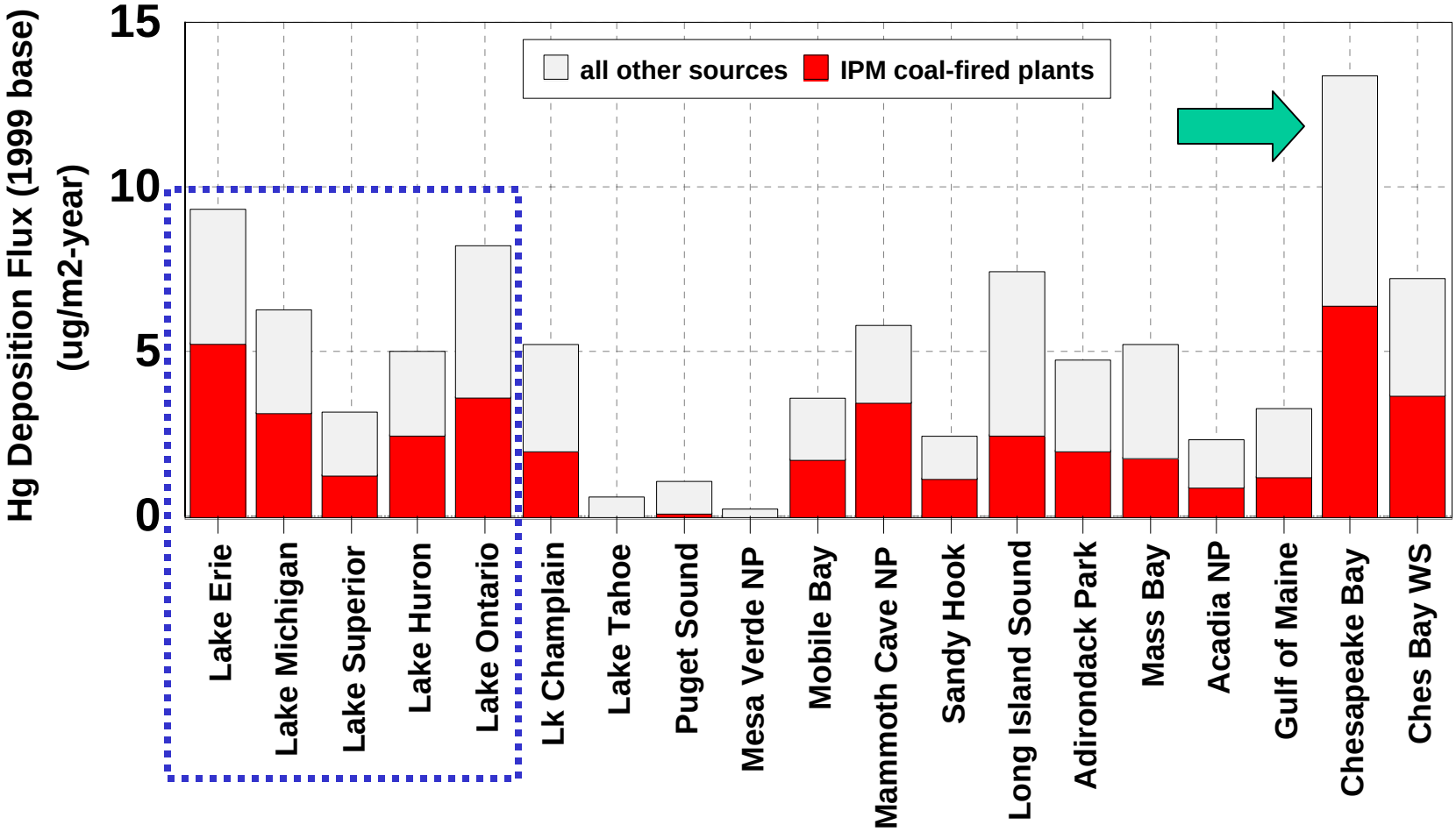
Emissions of Ionic Mercury (RGM) from Different Anthropogenic Source Sectors in Great Lakes States and Provinces (~1999-2000)
[Total RGM emissions = 13.4 metric tons/year]



Some Overall Results

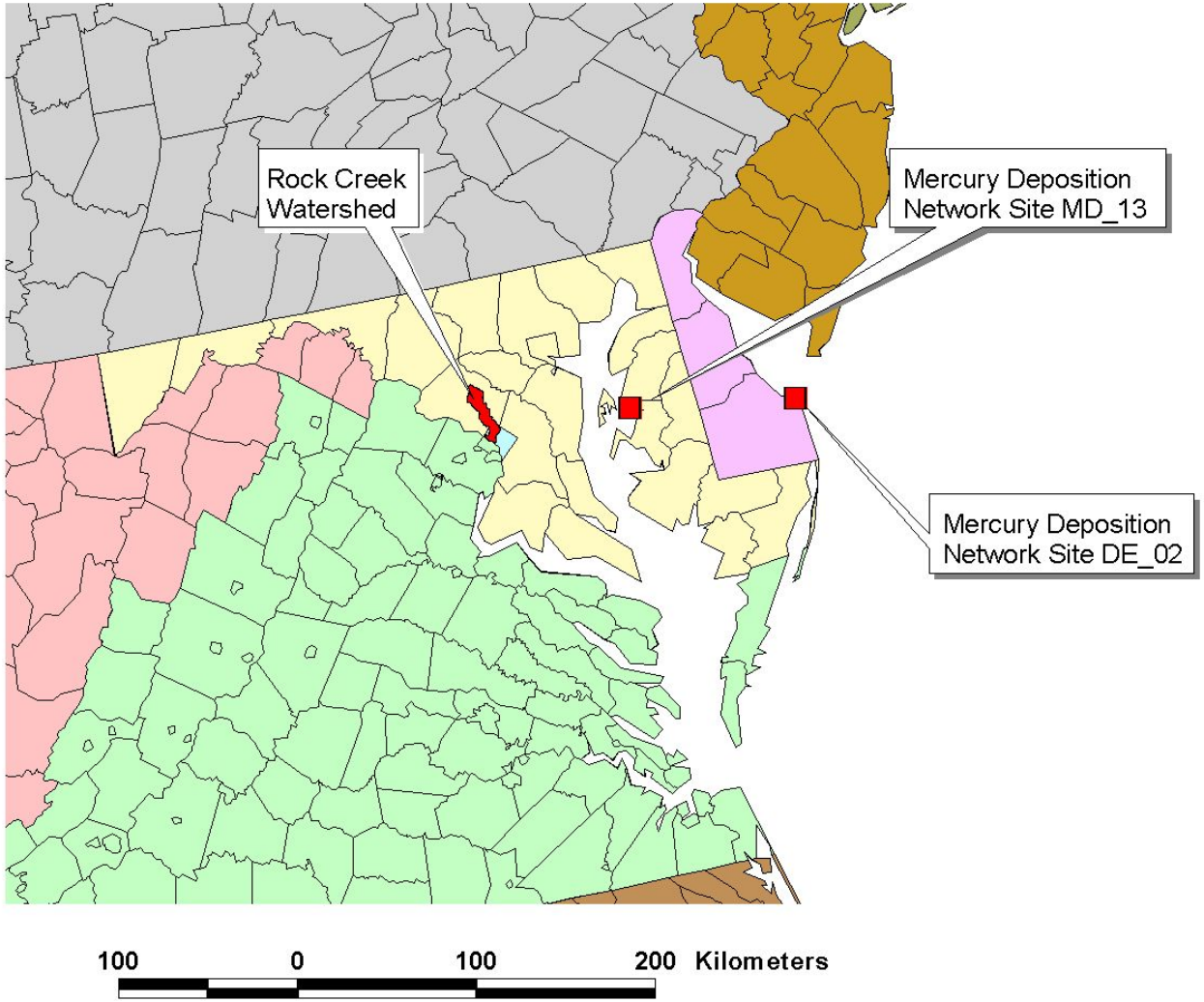
- **Modeling domain: North America**
- **U.S. and Canadian anthropogenic sources**
- **1996 meterology**
- **Model evaluation:**
  - **1996 emissions**
  - **1996 monitoring data**
- **Results: 1999 emissions**

Mercury deposition at selected receptors arising from 1999 base-case emissions from anthropogenic sources in the United States and Canada
(IPM coal fired plants are large coal-fired plants in the U.S. only)

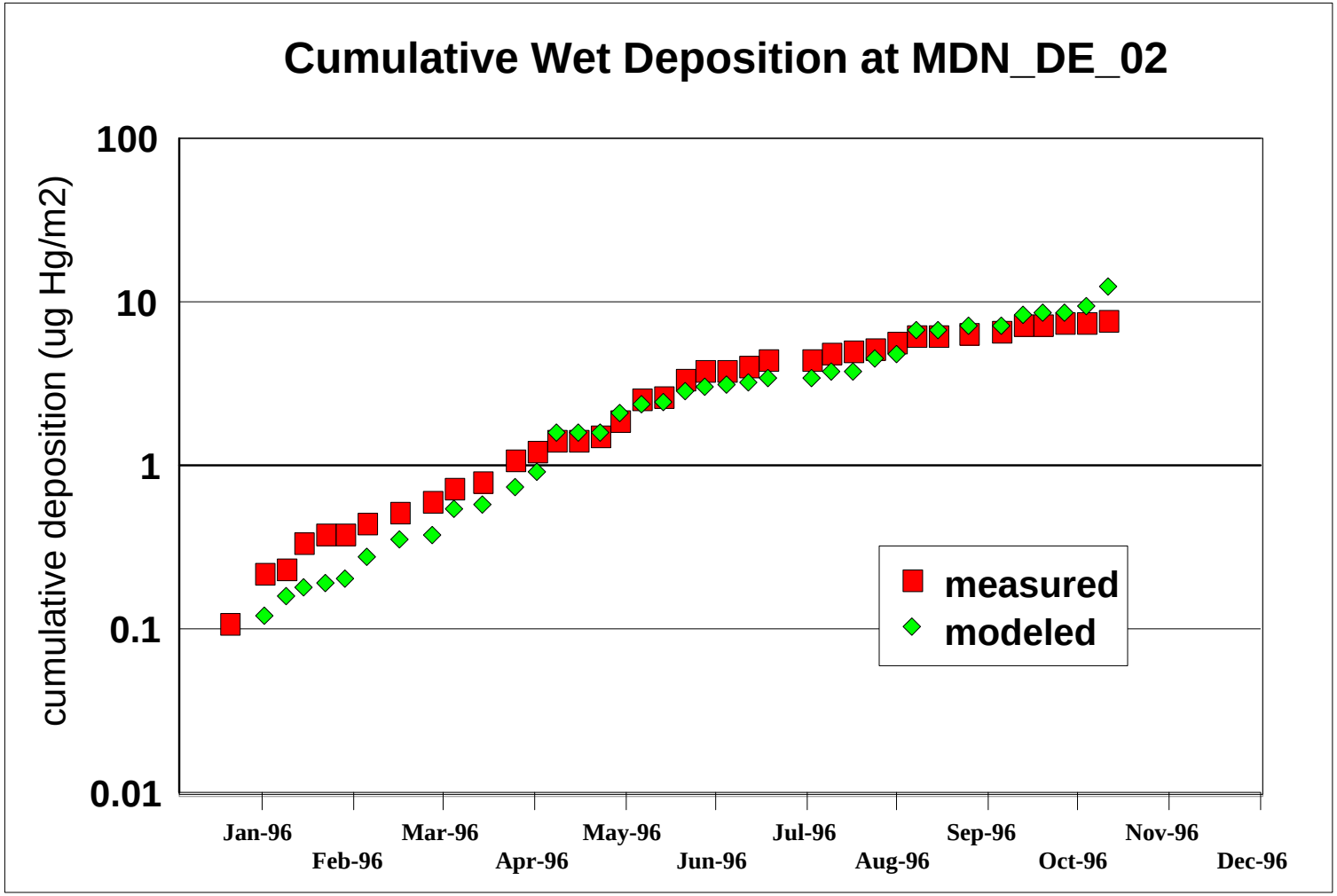


Model Evaluation

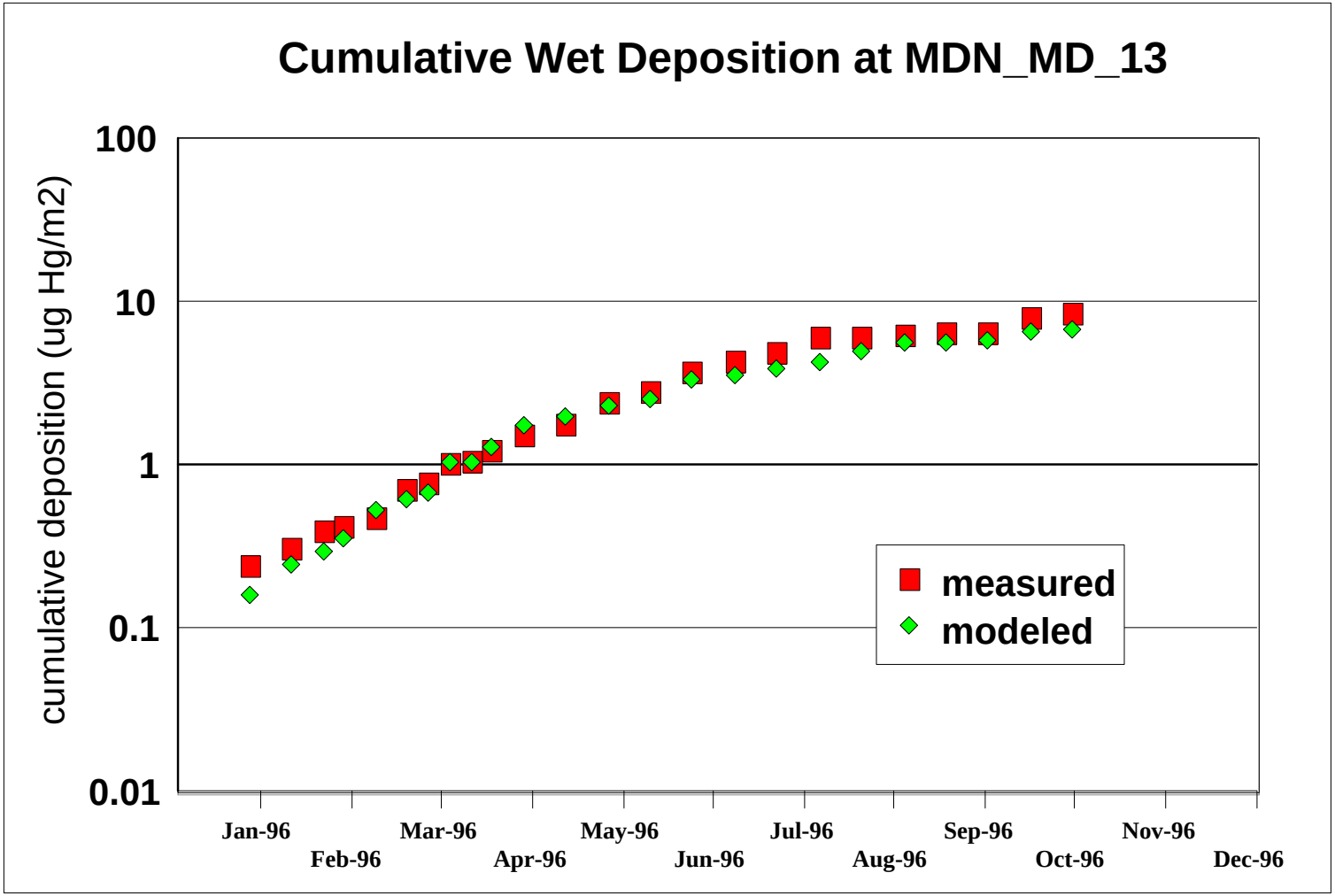
Mercury Deposition Network Sites with 1996 data in the Chesapeake Bay Region



Modeled vs. Measured Wet Deposition at Mercury Deposition Network Site DE_02 during 1996



Modeled vs. Measured Wet Deposition at Mercury Deposition Network Site MD_13 during 1996



Convention on Long-Range Transboundary Air Pollution

emep

Co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe

TECHNICAL REPORT
1/2003 June 2003

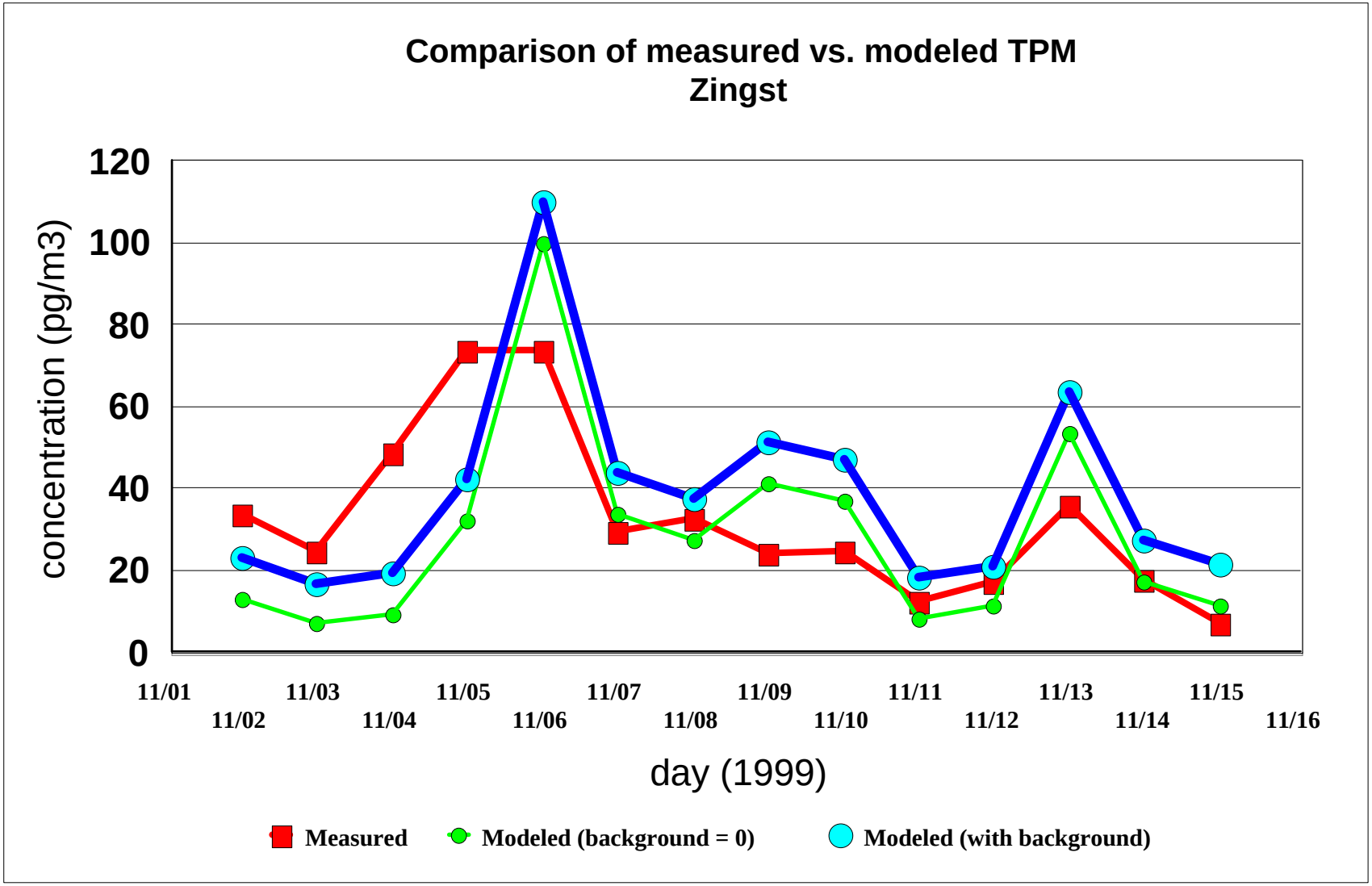
Intercomparison Study of Numerical Models for Long-Range Atmospheric Transport of Mercury

Stage II. Comparison of modeling results with observations obtained during short-term measuring campaigns

Technical Report 1/2003

A. Ryaboshapko, R. Artz,
R. Bullock, J. Christensen,
M. Cohen, A. Dastoor,
D. Davignon, R. Draxler,
R. Ebinghaus, I. Ilyin,
J. Munthe, G. Petersen,
D. Syrakov

msc-e


Comparison of measured vs. modeled TPM
Zingst
concentration (pg/m3)
120
100
80
60
40
20
0
11/01
11/02
11/03
11/04
11/05
11/06
11/07
11/08
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
day (1999)
Measured
Modeled (background = 0)
Modeled (with background)

•Models can be extremely useful, e.g., maybe the only way to develop comprehensive source receptor relationships…

- ***But we know the models are not perfect…***

- **When simulations don't agree with measurements, what is reason?**

  - ***There can be errors in simulation of***

    - **emissions**
    - **meteorology**
    - **dispersion**
    - **atmospheric chemistry**
    - **wet and dry deposition**

  - **How to tease out the most important reasons for discrepancies?**

- **How to tease out the most important reasons for discrepancies?**

  - **Critical to have sufficient data for model evaluation**
    - **Mercury Deposition Network very useful!**
    - **need network for ambient concentrations of RGM, Hg(p), Hg(0)**
    - **also -- data at different heights in the atmosphere**
    - **also – identification and quantification of individual RGM species**

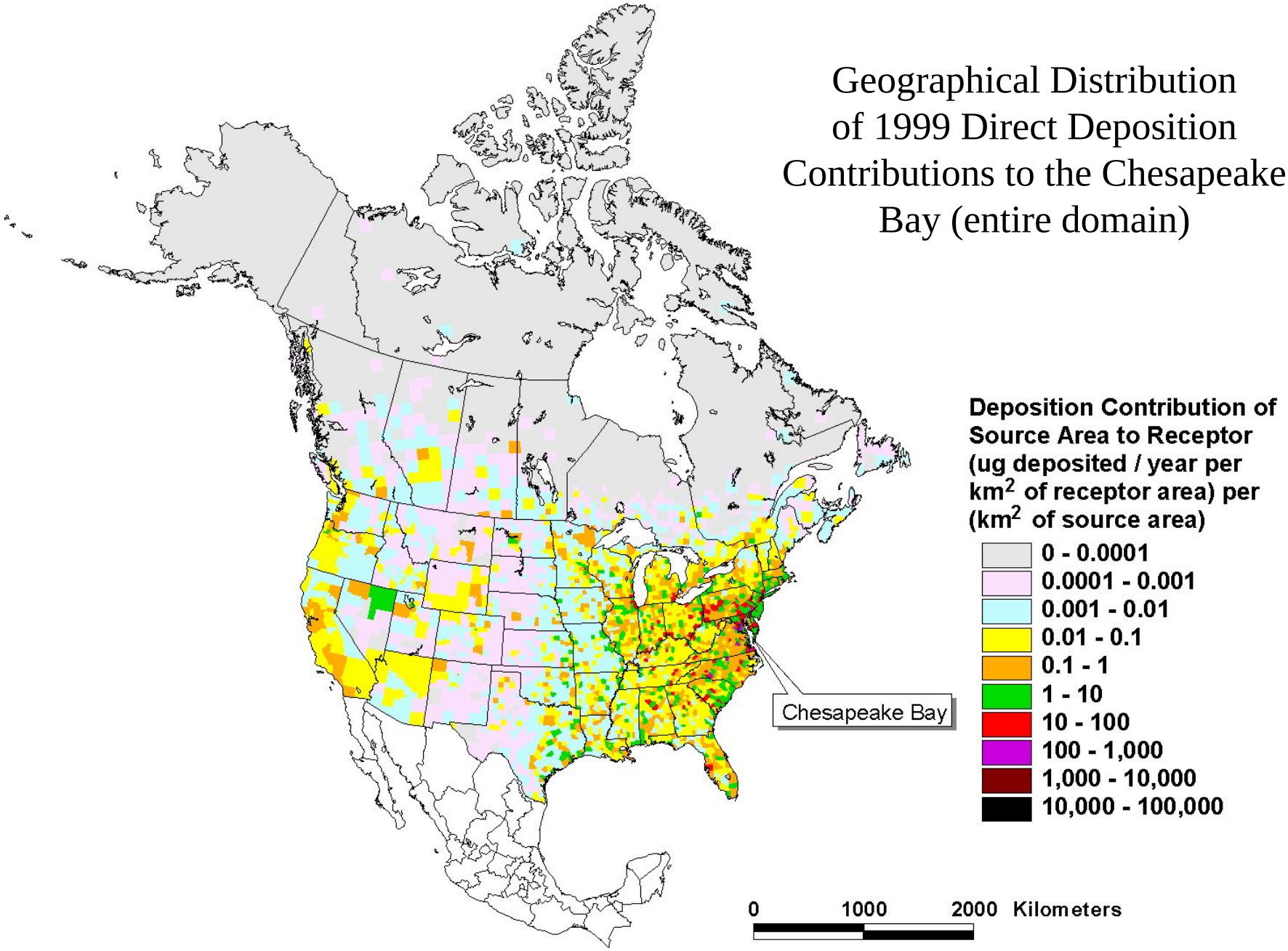
  - **Model intercomparison studies can be extremely useful**
    (why are they so hard to get funding for?)

  - **Does a model have to be perfect in order to be useful?**
    (No, often just need qualitatively reasonable results…)

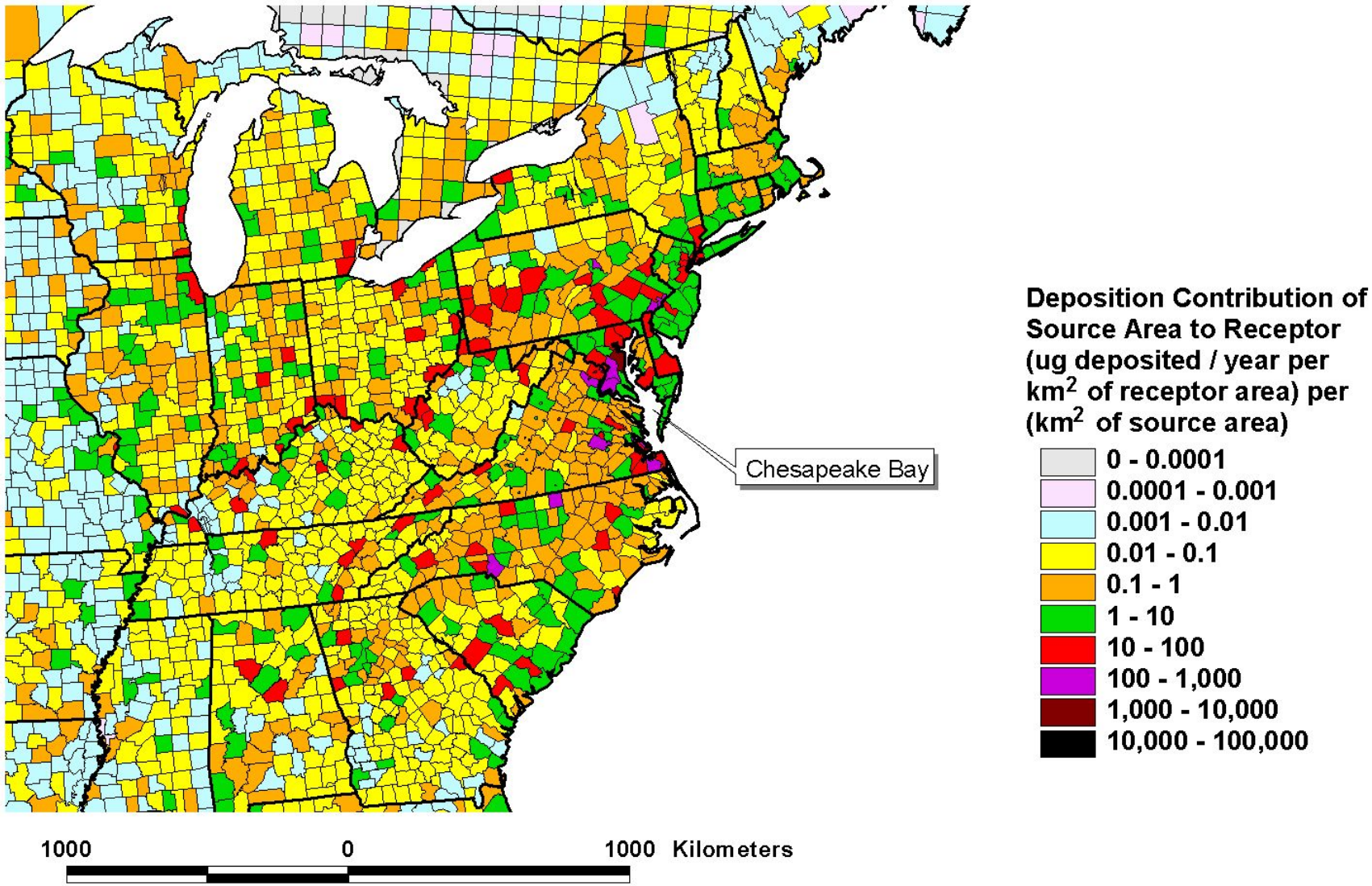
    Most if not all data and information used in decision-making has uncertainties – public health impacts, economic impacts (why do we demand perfection of models?)

1999 Results for Chesapeake Bay

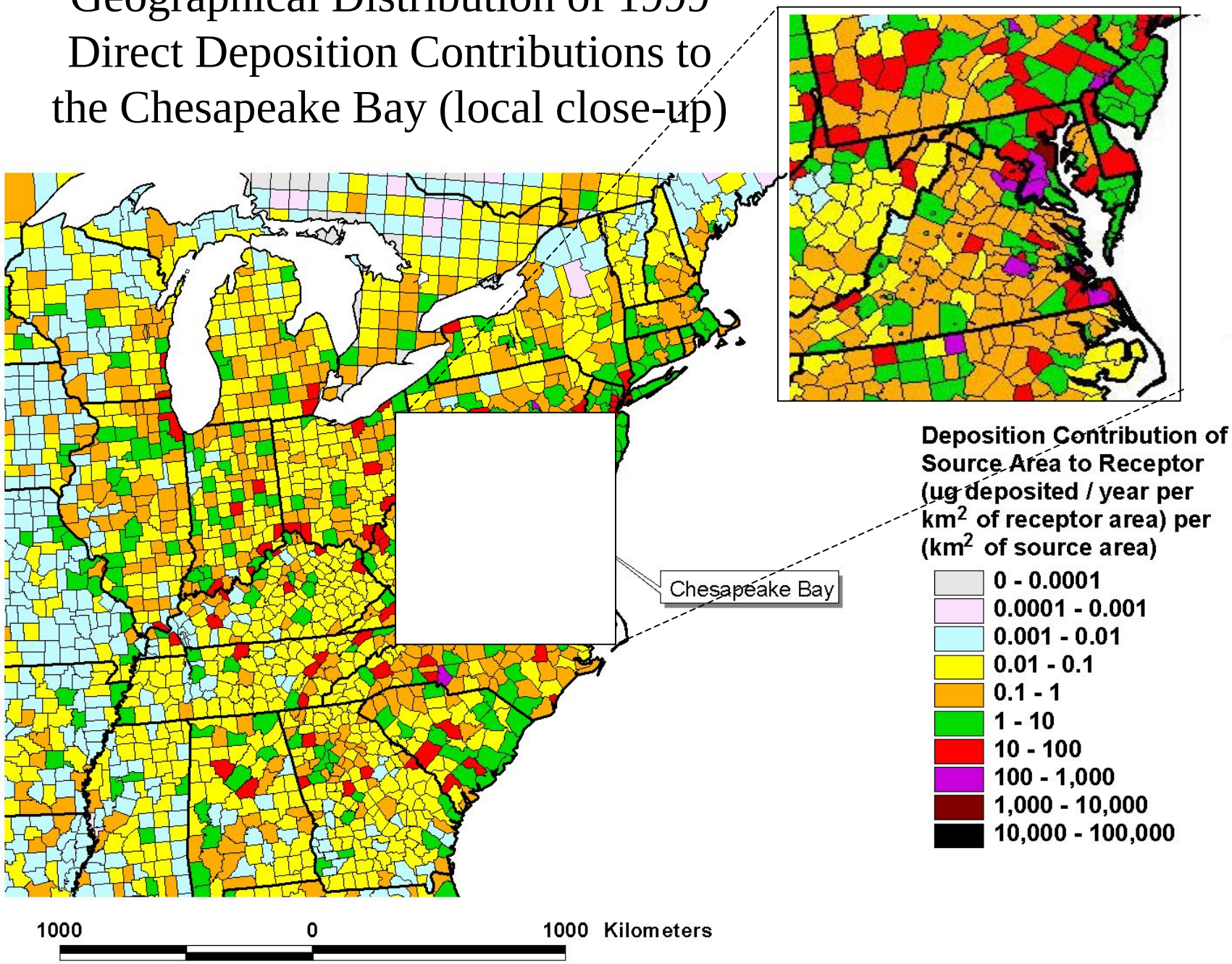
Geographical Distribution of 1999 Direct Deposition Contributions to the Chesapeake Bay (entire domain)



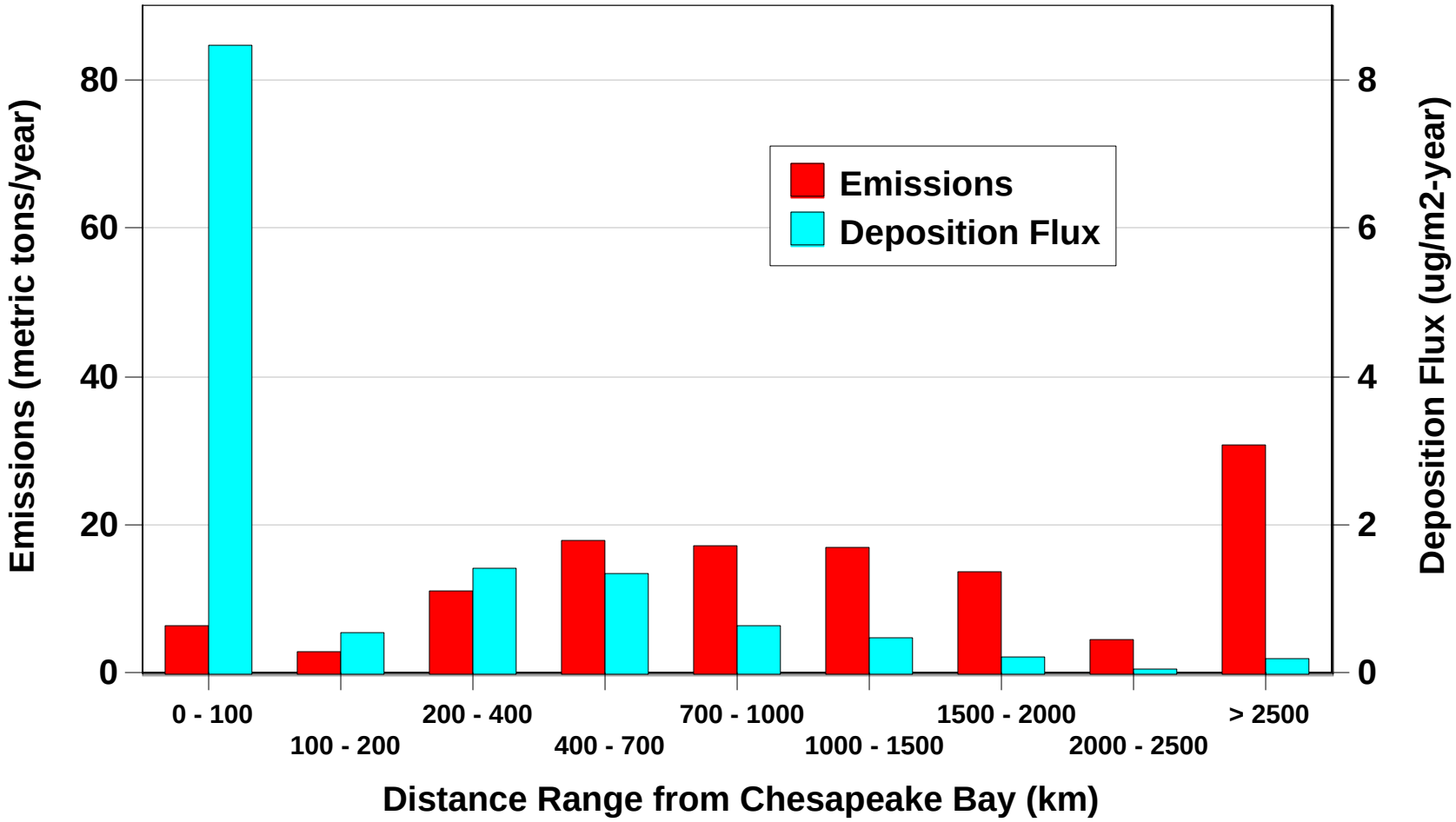
Geographical Distribution of 1999 Direct Deposition Contributions to the Chesapeake Bay (regional close-up)



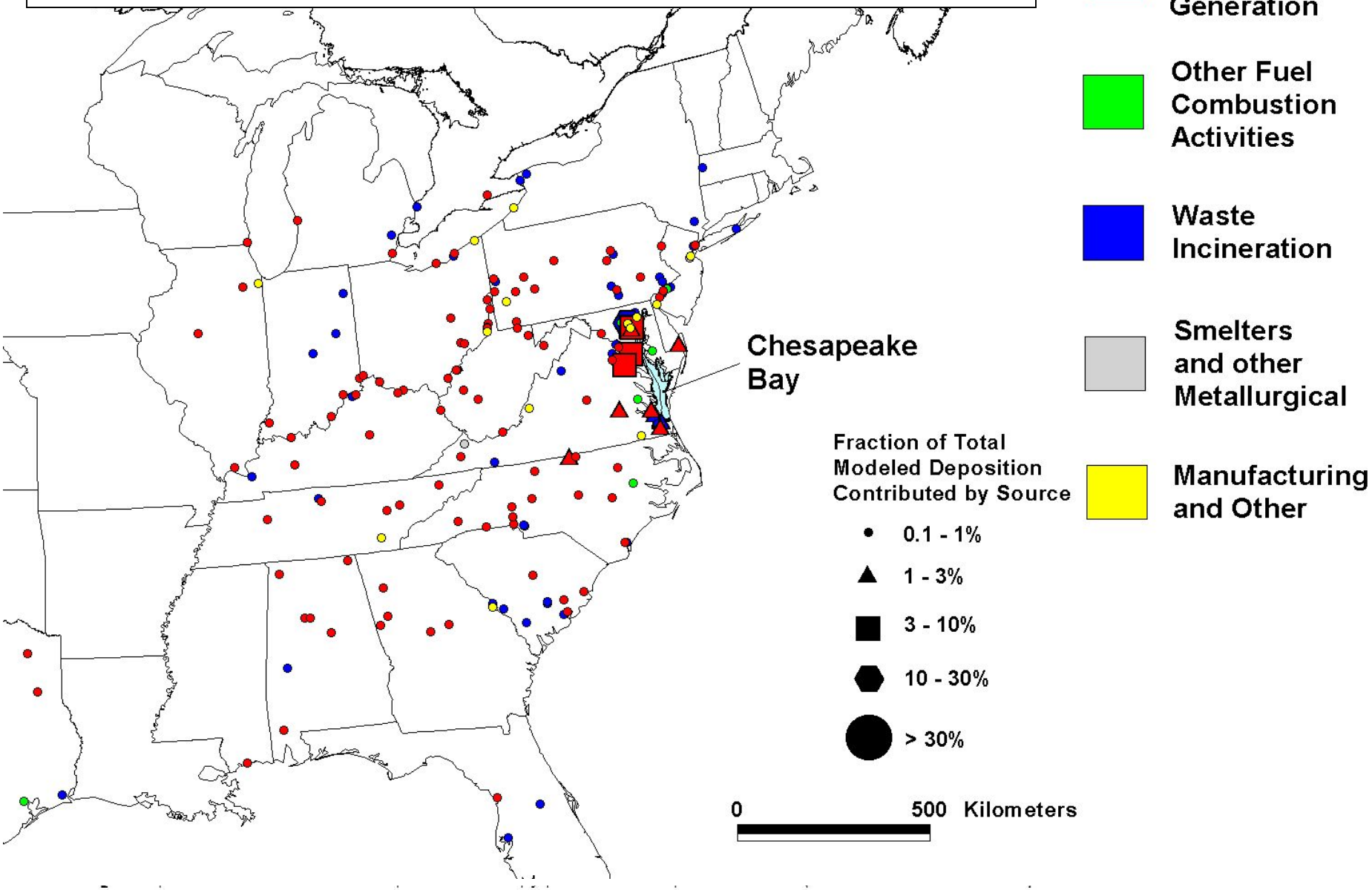
Geographical Distribution of 1999 Direct Deposition Contributions to the Chesapeake Bay (local close-up)



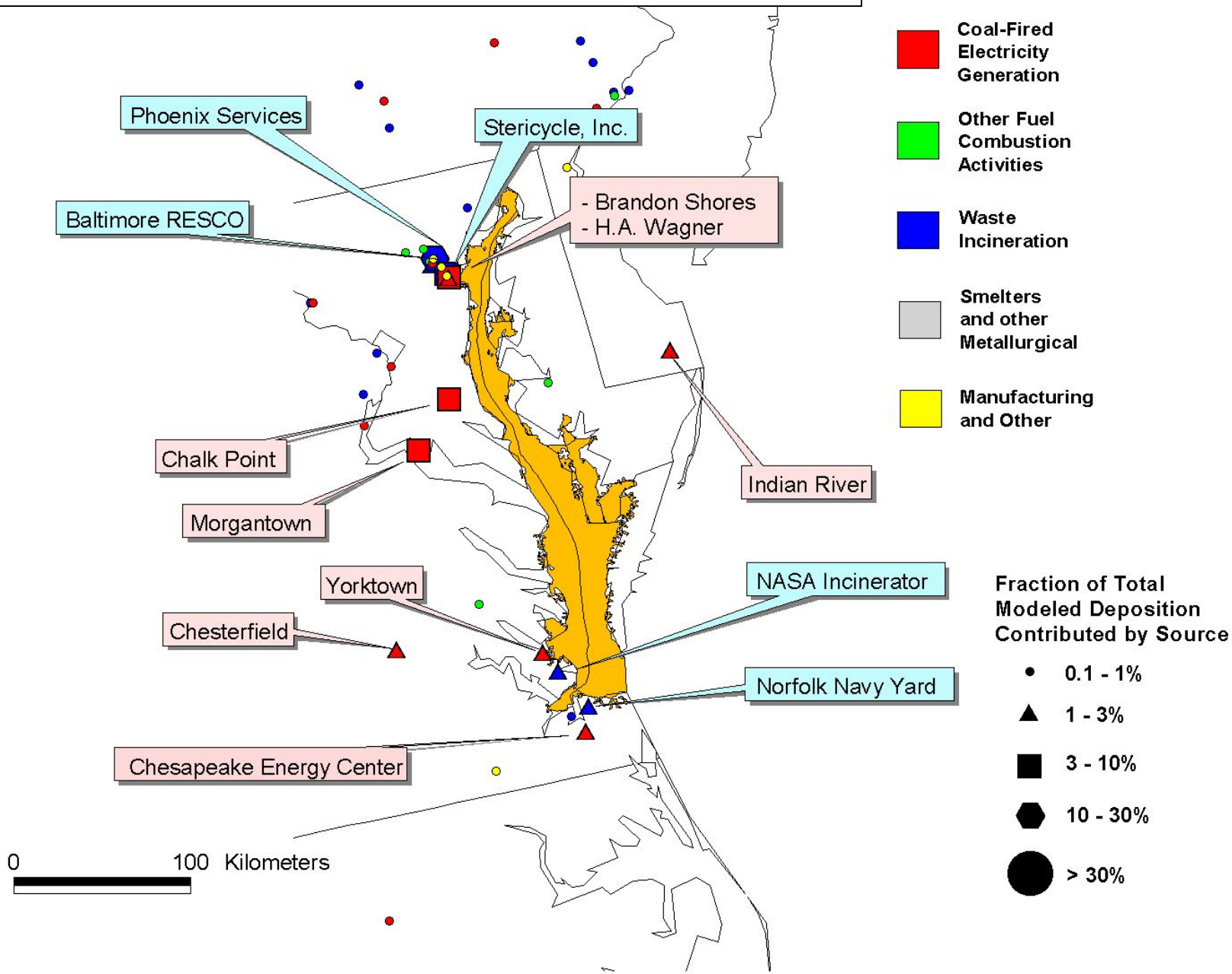
Emissions and Direct Deposition Contributions from Different Distance Ranges Away From the Chesapeake Bay



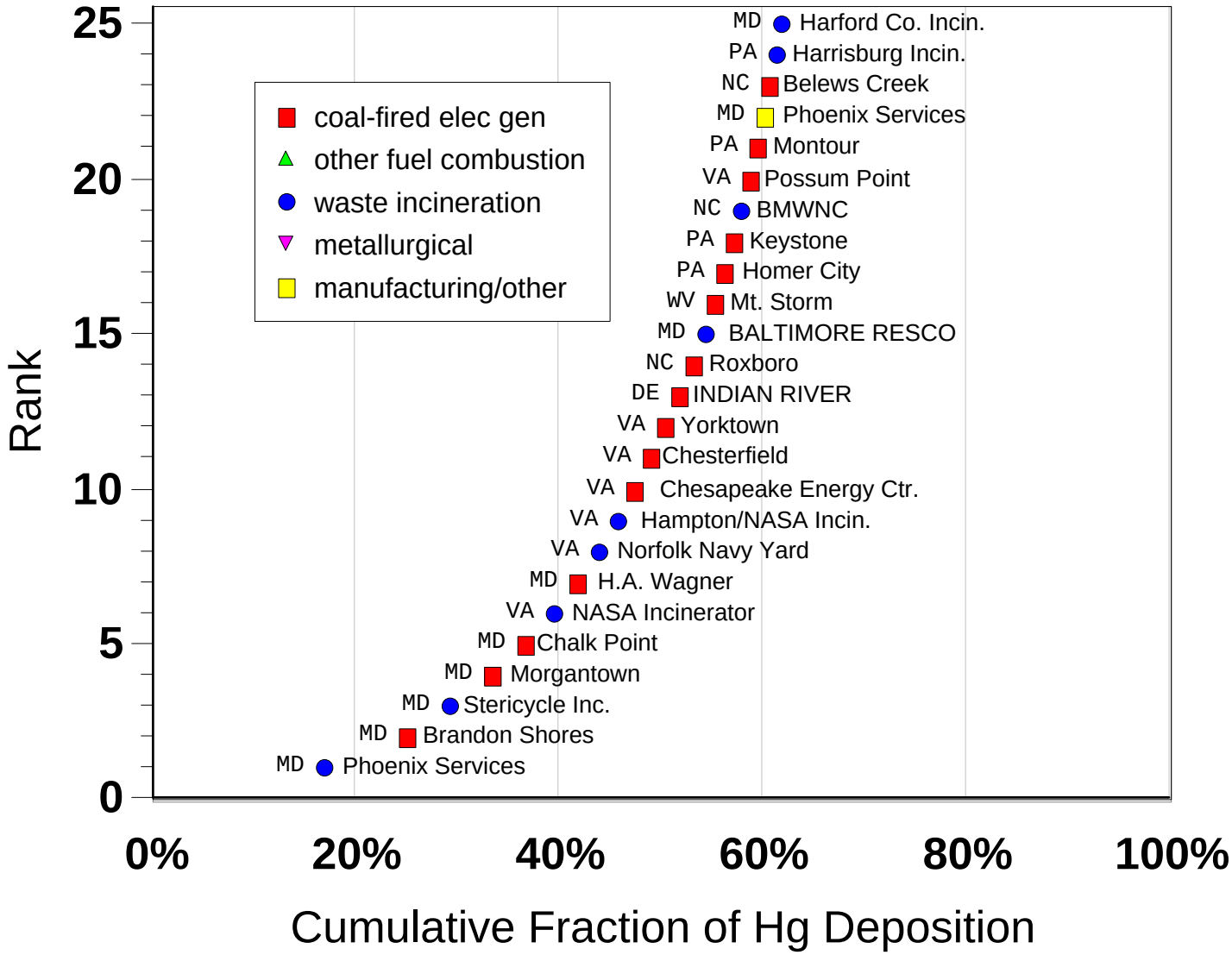
Largest Regional Individual Sources Contributing to 1999 Mercury Deposition Directly to the Chesapeake Bay



Largest Local Individual Sources Contributing to 1999 Mercury Deposition Directly to the Chesapeake Bay



Top 25 Contributors to 1999 Hg Deposition Directly to the Chesapeake Bay



Some Next Steps

- Use more highly resolved meteorological data grid
- Expand model domain to include global sources
- Simulate natural emissions and re-emissions of previously deposited Hg
- Additional model evaluation exercises ... more sites, more time periods, more variables *[Measurements underway in Chesapeake Bay region]*
- Sensitivity analyses and examination of atmospheric Hg chemistry (e.g. marine boundary layer, upper atmosphere)
- Dynamic linkage with ecosystem cycling models

Preliminary Results from Steubenville Hg Deposition Source Apportionment Study

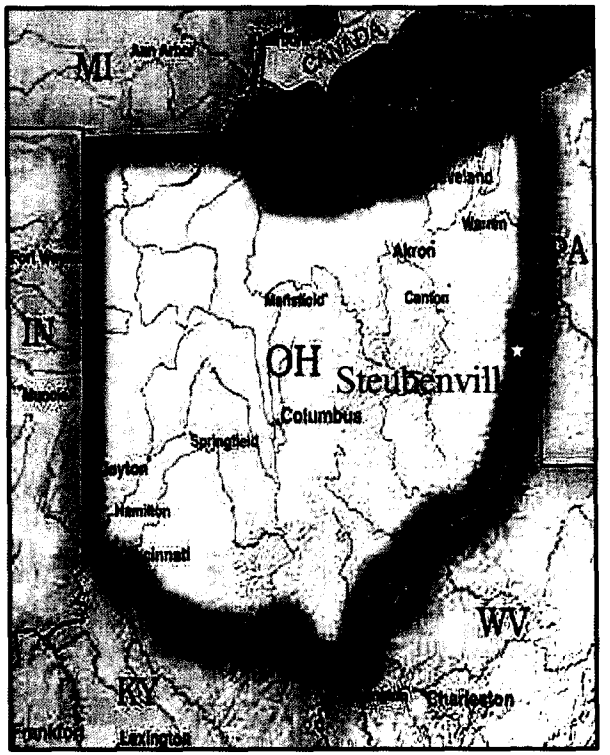
Brad Weiler, Tim Canfield

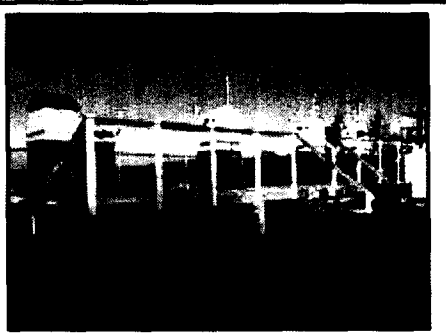
Purpose

- Provide a "Heads-Up" of the significant preliminary findings of the Steubenville study
  - Scientifically and Politically significant
- Seeking guidance on how to proceed with review and release of study results

Results

- Approximately 70% of Hg wet deposition at Steubenville site is attributable to local/regional fossil fuel (coal and oil) combustion sources
  - Not entirely attributable to electric utilities
- Preliminary results
  - Additional analysis to finalize results will be completed within a month

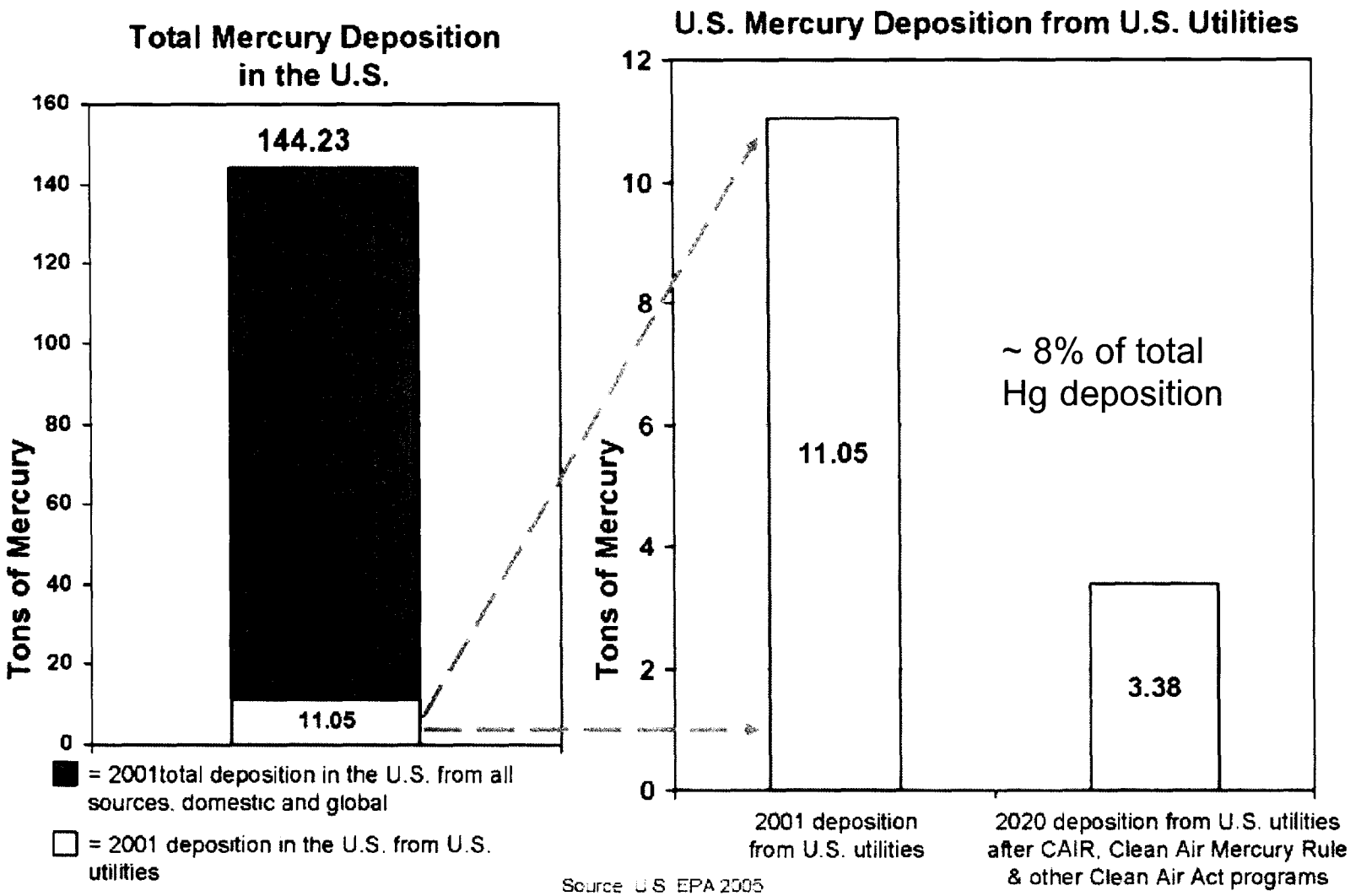




Significance of Results

- Current models (including those used by EPA for CAMR analyses) estimate a much lower local/regional source contribution to Hg deposition, on average
  - On average, approximately 8% of domestic Hg deposition estimated to be from domestic electric utility coal combustion
- Implications for potentially vulnerable areas (i.e., "Hotspots")
- Significant deposition decreases predicted for Steubenville area

Mercury Deposition in the U.S.

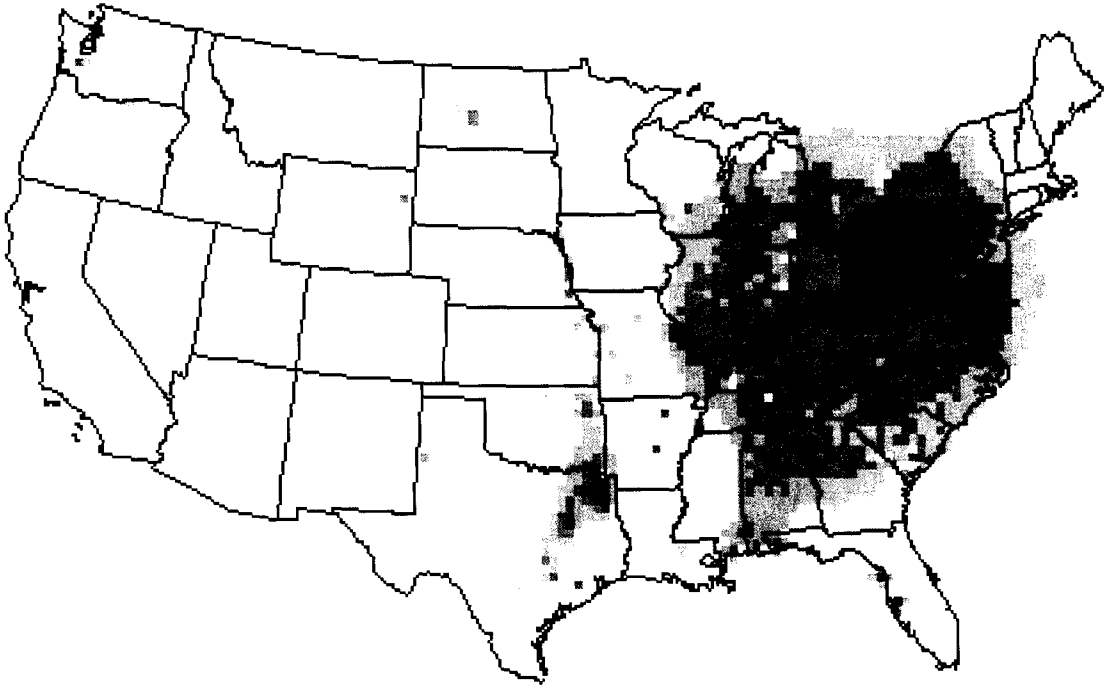


Source – US EPA Clean Air Mercury Rule website (8% note added)

Percent Change in Deposition from a 50% Reduction of Utility Emissions

Percent Change in Deposition

- 0.00 - 5.00
- 5.01 - 10.00
- 10.01 - 15.00
- 15.01 - 20.00
- 20.01 - 25.00
- 25.01 - 30.00
- 30.01 - 35.00
- 35.01 - 40.00
- 40.01 - 68.45



Explanation of Results

Are these results plausible?

- Yes
  - Steubenville site was chosen as because it was anticipated to be impacted by coal combustion
  - Results would appear to contradict EPRI claims of RGM to elemental Hg plume conversion

Note: Mercury is emitted from combustion sources in one of three species – reactive gaseous mercury (RGM), particulate mercury, and elemental mercury. RGM and particulate mercury contribute to local/regional deposition, while elemental mercury tends to be transported longer distances.

Why research similar to that presented previously?

- Recent convergence of newly available tools
  - New collection method
    - Precipitation-event-based sampler
  - Improved analytical method
    - Extremely low detection limits for trace elements
    - Use to measure potential co-pollutants (e.g., sulfur, selenium, vanadium)
  - State-of-the-art EPA receptor modeling tools
    - Statistical tools to identify relative source contributions
    - New releases of EPA UNMIX and Positive Matrix Factorization (PMF)
- Current mercury monitoring efforts do not collect data needed to conduct this type of analysis
  - Mercury Deposition Network (MDN) not designed for source apportionment studies
    - Weekly instead of event-based samples
    - In general, no co-located trace element measurements
- First time that state-of-the-art receptor models have been applied to mercury precipitation data

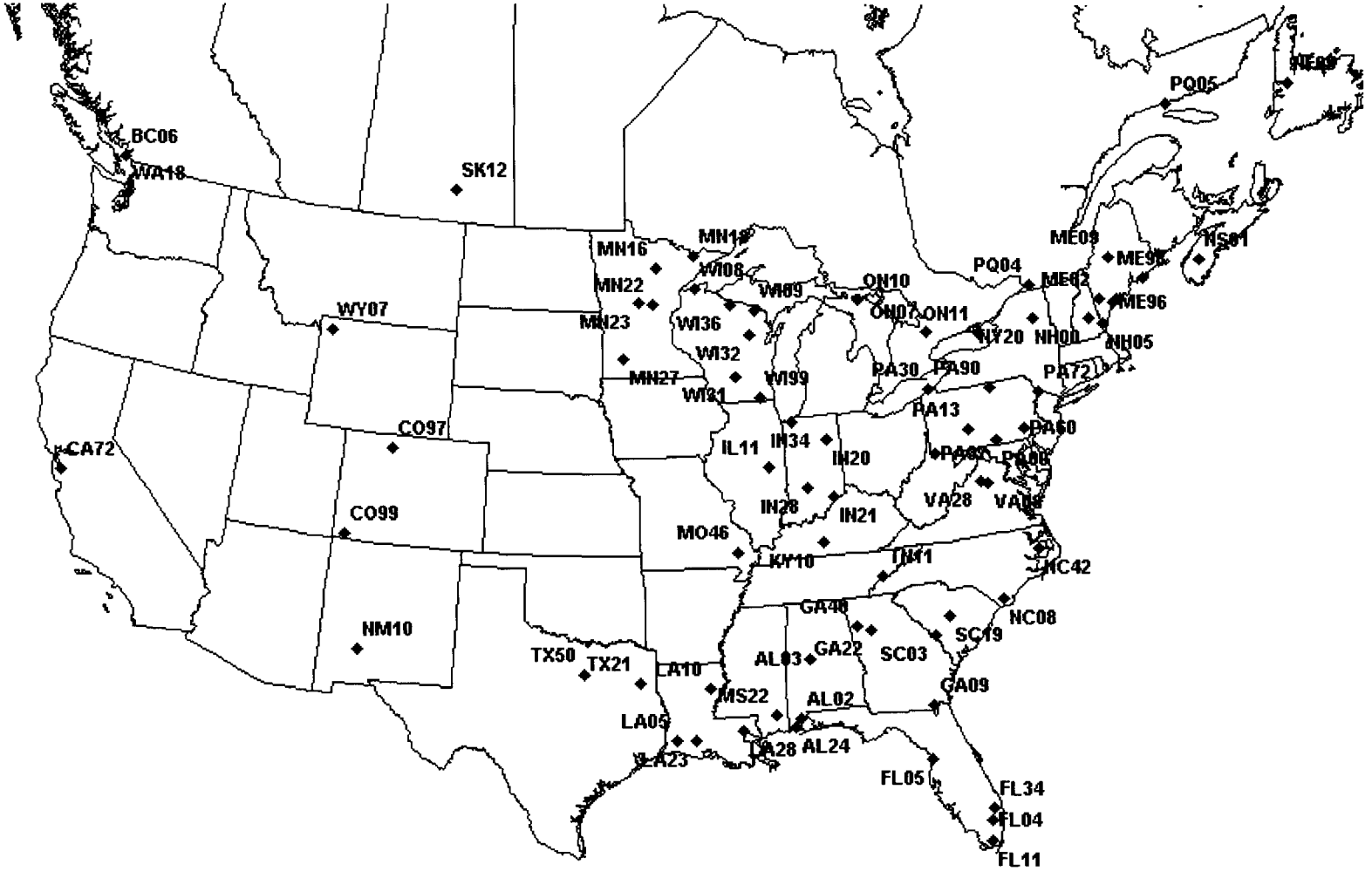
Are the results consistent with other studies?

- Consistent with studies conducted in south FL, but . . .
  - Local deposition was attributed to municipal and medical waste incinerators
  - Used more simplistic source apportionment tool

Why are estimated regional deposition values higher than those predicted in current air quality models?

- Lack of event-based empirical deposition data for model evaluation
- Deposition parameters in current models based and evaluated against Mercury Deposition Network (MDN) data
  - MDN sites generally located in rural areas
  - Emerging but limited empirical evidence of very high Hg concentrations/deposition in urban areas
    - Chicago, Charlotte, St. Louis, and Detroit
  - Potential underestimate of predicted deposition

National Atmospheric Deposition Program
Mercury Deposition Network



Why weren't these results available for CAMR analyses?

- Mercury MYP included 2004 APM
  - Initial efforts to run receptor models with one-year data set (2003) were not conclusive
  - APM delayed
- Completed second year of data collection (including QA/QC) in early April 2005
- Receptor models now producing conclusive results with two-year (2003 and 2004) data set

Will these results be replicated?

- Yes, because new tools are available and in use
  - New collection method
    - Developed by University of Michigan
    - Applied in Steubenville, at several other sites in Michigan, at one site in Vermont, and in Tampa, FL
  - Improved analytical method
    - University of Michigan has this capability
  - State-of-the-art receptor models
    - New EPA Receptor models are publicly available

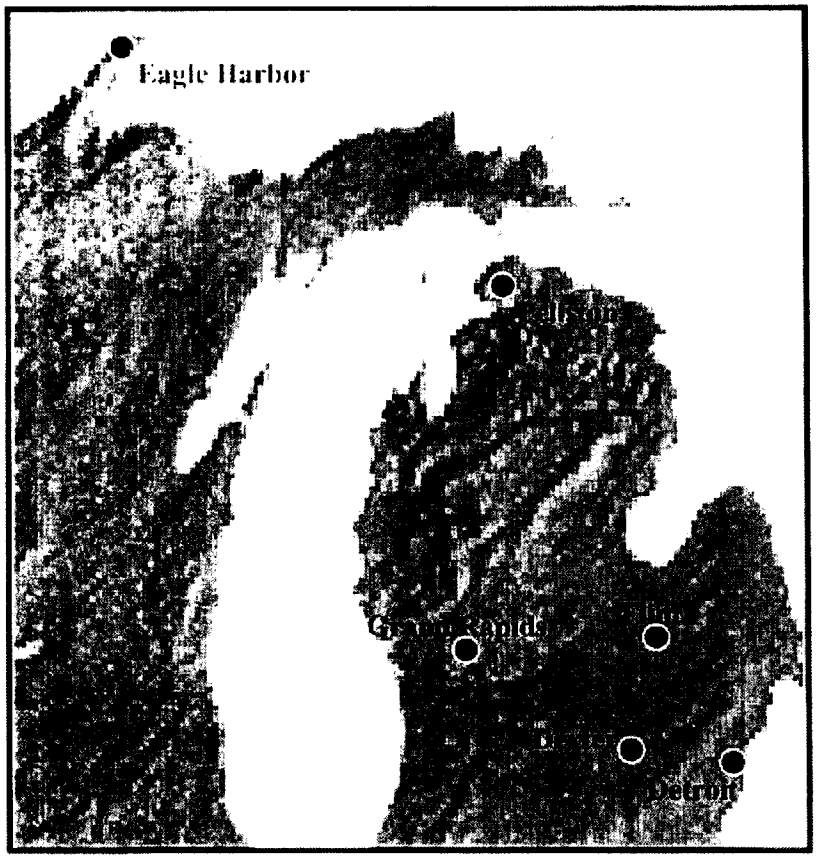


Figure 1. Location of Atmospheric Mercury Monitoring Sites in Michigan.

Planned Next Steps

- Additional data analyses
  - Complete review of receptor modeling to finalize study results
  - Refined analyses of peak events
    - Explore meteorology data
    - Identify specific source regions and/or sources contributing to deposition events in Steubenville
- Prepare materials for EPA (OAR in particular) dissemination
- Prepare manuscript for peer-reviewed journal submission
- Future work
  - Conduct similar studies in other existing locations
    - North-South gradient in Ohio Valley (data from Univ of Mich)
    - East-West gradient using sites in Vermont (data from Univ of Mich)
    - Tampa, FL
  - Extend analysis to mercury dry deposition
  - Continue monitoring in Steubenville
    - Location for Clean Air Mercury Rule (CAMR) Accountability?
  - Integrate results into air quality models (CMAQ)

Issues for Discussion

- How and when should we disseminate the results of this study within EPA (particularly to OAR)?

- Do we need to utilize additional peer-review mechanisms beyond journal submission and review?

Supplemental Information

Steubenville Study Approach
An Overview of Source Apportionment
Additional information on new sources
Attachment

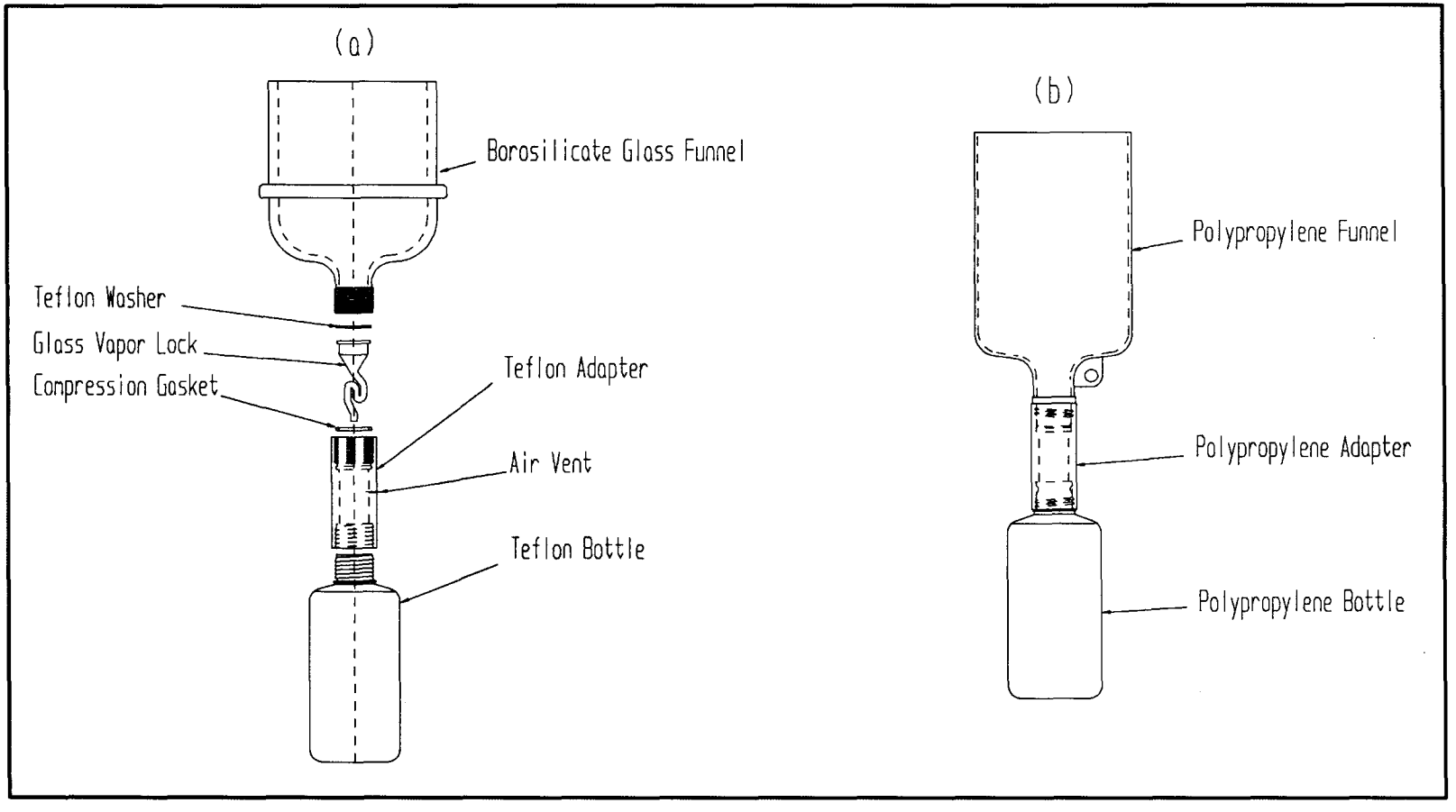
Study Approach

- Site location / duration
  - Steubenville, OH – anticipated to impacted by coal combustion sources
  - 4-year study
    - 2-years of data collected to date (2003 and 2004)
- Cooperative agreement with the University of Michigan
- Collecting detailed measurements
  - Precipitation event-based deposition sampling
  - Potential source co-pollutants (trace elements)
  - Meteorology
- Applying state-of-the-art receptor models
  - Latest version of EPA models – UNMIX and PMF
  - First time modeling approaches applied to Hg precipitation data

An Overview of Source Apportionment

- Relating source emissions to their quantitative impact on environmental concentrations (i.e., ambient or deposition) is referred to as source apportionment
- Two approaches to source apportionment
  - Dispersion modeling (e.g., CMAQ)
    - Combines emissions, chemistry, and meteorology information to relate sources to predicted ambient concentrations
  - Receptor modeling
    - Uses environmental measurements and statistics to identify sources or source categories impacting the receptor.
- Single-sample receptor models
  - Require source profiles or "fingerprints"
  - Example – Chemical Mass Balance (CMB)
- Multivariate receptor models
  - Require many samples (100 or more)
  - Source profile information not needed
  - Examples – UNMIX and Positive Matrix Factorization (PMF)

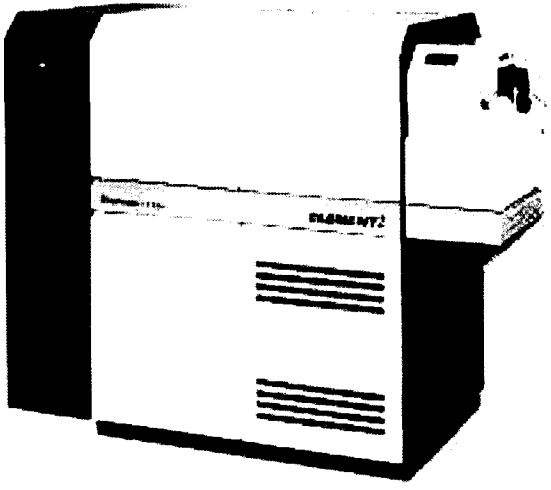
Wet-Only Precipitation Collection



* Landis and Keeler *Environ. Sci. Technol.*, **1997**, 31, 2610-2615

High Resolution ICP-MS Capability
(Precipitation & Aerosol Samples)

- Low Resolution
  - Li, Be, Rb, Sr, Mo, Ag, Cd, In, Sn, Sb
    Cs, Ba, La, Ce, Nd, Sm, W, Tl, Pb, U
- Medium Resolution
  - Na, Mg, Al, P, S, Ca, Sc, Ti, V, Cr
    Mn, Fe, Co, Ni, Cu, Zn
- High Resolution
  - K, As, Se
- Stable Isotope Ratios
  - Pb



Statistical Receptor Model Development

- **UNMIX**
  - Multi-linear model (Ron Henry – USC)
  - Usually requires at least 100 samples
  - Does not use data below MDL
  - Generates source profiles and uncertainties
- **Positive Matrix Factorization (PMF)**
  - Multi-linear model (Phil Hopke – Clarkson University)
  - Usually requires at least 100 samples
  - Uses data below MDL
  - Incorporates uncertainties and weights individual data points
  - Generates source profiles and uncertainties

OFFICE OF INSPECTOR GENERAL

Catalyst for Improving the Environment

Evaluation Report

Monitoring Needed to Assess Impact of EPA's Clean Air Mercury Rule on Potential Hotspots

Report No. 2006-P-00025

May 15, 2006

OIG-II

Report Contributors:

Rick Beusse
Carolyn Blair
Hilda Canes
Susan Charen
Sarah Fabirkiewicz
James Hatfield
Erica Hauck
James Van Orden

Abbreviations

CAMR	Clean Air Mercury Rule
CMAQ	Community Multiscale Air Quality
EPA	Environmental Protection Agency
Hg	Mercury
IPM	Integrated Planning Model
km	kilometer
MACT	Maximum Achievable Control Technology
MDN	Mercury Deposition Network
mg/kg	milligram per kilogram
OIG	Office of Inspector General

Cover photo: A fisherman holding a walleye, a predator fish for which mercury contamination is a concern (photo courtesy EPA).

U.S. Environmental Protection Agency
Office of Inspector General

2006-P-00025
May 15, 2006

At a Glance

Catalyst for Improving the Environment

Why We Did This Review

In support of its Clean Air Mercury Rule (CAMR), the Environmental Protection Agency (EPA) conducted a detailed analysis of mercury emissions and deposition. EPA concluded that "utility-attributable" hotspots would not occur after implementation of CAMR's mercury trading program. This evaluation assesses the basis for EPA's conclusion.

Background

About 40 percent of U.S. man-made airborne mercury is emitted from coal-fired utilities. EPA revised a previous finding that mercury emissions from coal-fired utilities be regulated with a Maximum Achievable Control Technology standard. Instead, EPA adopted a cap-and-trade program to reduce mercury emissions. Several State agencies and environmental groups objected to these actions. One concern was that a cap-and-trade program could result in localized areas with unacceptably high levels of mercury, or "hotspots."

For further information, contact our Office of Congressional and Public Liaison at (202) 566-2391.

To view the full report, click on the following link: www.epa.gov/oig/reports/2006/20060515-2006-P-00025.pdf

Monitoring Needed to Assess Impact of EPA's Clean Air Mercury Rule on Potential Hotspots

What We Found

EPA brought significant scientific, technical, and modeling expertise to bear in developing a specific methodology to consider the potential for mercury hotspots. Several uncertainties associated with key variables in the analysis could affect the accuracy of the Agency's conclusion that the Clean Air Mercury Rule (CAMR) will not result in "utility-attributable" hotspots. We noted:

- gaps in available data and science for mercury emissions estimates,
- limitations with the model used for predicting mercury deposition,
- uncertainty over how mercury reacts in the atmosphere, and
- uncertainty over how mercury changes to a more toxic form in waterbodies.

Two recent studies support the need for additional monitoring to ensure that EPA's analysis has properly estimated the contribution of local, regional, and global sources on U.S. deposition. These studies are "*Mechanisms of Mercury Removal by O_3 and OH in the Atmosphere,*" published in *Atmospheric Environment* in June 2005; and "*Sources of Mercury Wet Deposition in Eastern Ohio, USA,*" submitted for publication in a scientific journal in February 2006. Results of both studies were not available until after EPA issued CAMR in March 2005, and thus could not have been considered in EPA's deliberations on CAMR. Although EPA indicated in CAMR that it would monitor the impact of the cap-and-trade rule on mercury deposition, the Agency has not yet developed a monitoring plan for this purpose. Without field data from an improved monitoring network, EPA's ability to advance mercury science will be limited and "utility-attributable" hotspots that pose health risks may occur and go undetected.

Based on our interpretation of CAMR, EPA could not take action to mitigate a mercury hotspot unless the Agency first determined that the hotspot was solely "utility-attributable." Therefore, EPA could not require additional utility emission reductions if utilities contributed significantly, but not solely, to a mercury hotspot. This could limit EPA's ability to mitigate human health hazards by reducing potentially harmful levels of mercury in waterbodies and fish tissue. This could also limit EPA's ability to reduce the number of waterbodies with fish consumption advisories.

What We Recommend

We recommend that EPA develop and implement a mercury monitoring plan to (1) assess the impact of CAMR, if adopted, on mercury deposition and fish tissue; and (2) evaluate and refine mercury estimation tools and models. Further, if CAMR is adopted after the rule reconsideration process is complete, we recommend that EPA clarify in the final rule that the "utility-attributable" hotspot definition does not establish a prerequisite for making future revisions to CAMR. In response to the draft report, the Agency agreed that additional mercury monitoring is needed and explained that CAMR does not establish the "utility-attributable" hotspot definition as a prerequisite for future changes to CAMR.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

OFFICE OF
INSPECTOR GENERAL

May 15, 2006

MEMORANDUM

SUBJECT: Monitoring Needed to Assess Impact of EPA's Clean Air Mercury Rule on Potential Hotspots
Report No. 2006-P-00025

TO: William L. Wehrum
Acting Assistant Administrator for Air and Radiation

This is our report on the subject evaluation conducted by the Office of Inspector General (OIG) of the U.S. Environmental Protection Agency (EPA). This report contains findings that should help EPA to better monitor the impact of the Clean Air Mercury Rule and refine performance standards under the rule, if necessary. This report represents the opinion of the OIG and the findings in this report do not necessarily represent the final EPA position. Final determinations on matters in the report will be made by EPA managers in accordance with established procedures.

Action Required

In accordance with EPA Manual 2750, as the action official, you are required to provide a written response within 90 days of the final report date. The response should address all recommendations. For the corrective actions planned but not completed by the response date, please describe the actions that are ongoing and provide a timetable for completion. Where you disagree with a recommendation, please provide alternative actions for addressing the findings reported.

We appreciate the efforts of EPA managers and staff in working with us to develop this report. If you or your staff have any questions regarding this report, please contact me at 202-566-0847, or Rick Linthurst at 919-541-4909.

Sincerely,

Bill A. Roderick
Acting Inspector General

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At a Glance

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Scope and Methodology 5

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Chapter 1
Introduction

Purpose

A prior Environmental Protection Agency (EPA) Office of Inspector General (OIG) report cited concerns about EPA's limited assessment of the potential for mercury hotspots resulting from a cap-and-trade program under the Clean Air Mercury Rule (CAMR). We issued this prior report, *Additional Analyses of Mercury Emissions Needed Before EPA Finalizes Rules for Coal-Fired Electric Utilities* (Report No. 2005-P-00003), on February 3, 2005. In support of CAMR, EPA conducted a detailed analysis of mercury emissions and deposition and concluded that "utility-attributable" hotspots would not occur after implementation of the mercury emissions trading program.

EPA's Water Quality Trading Assessment Handbook defines hotspots as "localized areas with unacceptably high levels of pollutants." In this evaluation report, however, a hotspot is a waterbody containing consumable fish with elevated levels of methylmercury in their tissues.

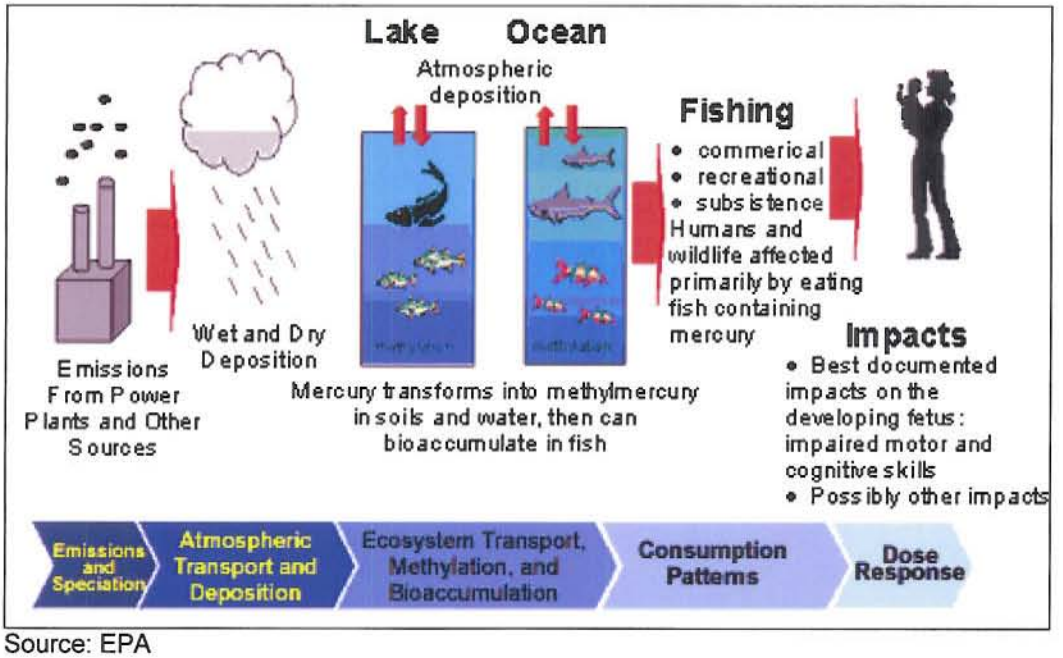
We conducted this evaluation to assess the basis for the Agency's determination that CAMR would not result in "utility-attributable" hotspots.

Background

Mercury (Hg) is released into the atmosphere through natural processes and through human activities, such as combustion processes. Once emitted, atmospheric mercury undergoes several chemical and physical processes and can then be deposited to the ground or waterbodies via wet or dry processes. In wet deposition, mercury is deposited by precipitation, such as rain or snow. In dry deposition, mercury settles to the earth's surface and sticks to or is absorbed by trees, soil, water, or other surfaces. The largest source of airborne mercury emissions in the United States is the coal-fired electric utilities industry, representing an estimated 40 percent of total U.S. man-made airborne mercury.

Although airborne mercury is generally not considered to be a serious health concern, once mercury enters freshwater and salt-water bodies, it can bioaccumulate in fish and other animal tissues in its more toxic form, methylmercury. As methylmercury bioaccumulates in the food chain, its concentration becomes increasingly higher in animals at the top of the food chain (such as larger predatory fish) that consume smaller, contaminated organisms. Figure 1-1 illustrates the exposure pathway of mercury.

Figure 1-1: How Mercury Enters the Environment



Source: EPA

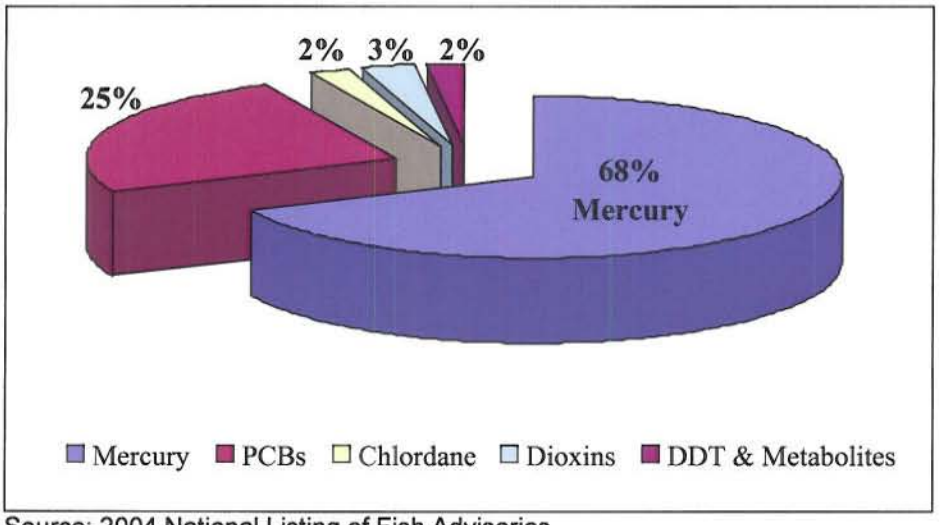
Fish consumption is the main route by which methylmercury harms human health. Excessive human exposure to methylmercury has been associated with severe detrimental neurological and developmental health effects. Research has shown that the developing fetus is at risk for impaired motor and cognitive skills. Thus, exposure to mercury by women of child-bearing age is of particular concern.

Most U.S. Fish Advisories Due to Mercury Contamination

When levels of chemical contamination in fish are considered unsafe, States, tribes, and territories can issue consumption advisories that may recommend that people limit or avoid eating certain species of fish caught in certain places. Each State sets its own criteria and decides which bodies of water to monitor. Monitored waterbodies may vary from year to year. Fish advisories are voluntary State recommendations not governed by Federal regulations. In 2004, 44 States issued fish advisories for mercury. The number of mercury-related fish advisories continues to rise as States increase fish tissue testing.

EPA recently reported in its 2005 *Performance and Accountability Report* that the Agency did not meet its goal of reducing the number of overall fish advisories by at least 1 percent from 2002 levels. From 2003 to 2004, the number of mercury advisories rose from 2,362 to 2,436, or 3.1 percent. According to the 2004 National Listing of Fish Advisories, the vast majority (68 percent) of fish advisories in the United States are due to mercury contamination, as illustrated in Figure 1-2.

Figure 1-2: Percent of Fish Advisories for Each of the Top Five Bioaccumulative Contaminants in 2004



Source: 2004 National Listing of Fish Advisories

CAMR First Rule for Mercury Emissions from Coal-Fired Utilities

On March 15, 2005, EPA issued CAMR, which established the country's first regulation of mercury emissions from coal-fired power plants. CAMR uses a declining cap-and-trade approach to regulating coal-fired utilities under Section 111 of the Clean Air Act by setting a fixed national cap. Utilities can buy and sell credits among one another in a national emissions market. Utilities that cannot cost-effectively reduce emissions may buy allowances from units that reduced emissions below established allowance limits. Under CAMR, an interim national cap of 38 tons per year becomes effective in 2010 and a final annual cap of 15 tons becomes effective in 2018. EPA's first cap is based on mercury reductions expected to be achieved as a co-benefit of implementing the Clean Air Interstate Rule, issued in March 2005. That rule requires utilities to take actions to reduce emissions of sulfur dioxide and nitrogen oxides, and those actions are also projected to reduce mercury emissions.

EPA Revised its Prior Regulatory Finding Regarding Utilities

To use a cap-and-trade program to regulate coal-fired utilities, EPA first had to revise a December 2000 regulatory finding[1] that indicated it was appropriate and necessary to regulate coal-fired utilities under Section 112 of the Clean Air Act. This finding required EPA to regulate utilities using a Maximum Achievable Control Technology (MACT) standard. MACT standards are

[1] *Regulatory Finding on the Emissions of Hazardous Air Pollutants From Electric Utility Steam Generating Units,* December 20, 2000; Vol. 65, No. 245.

industry-specific, technology-based standards designed to reduce hazardous air pollutant emissions. These standards can require facility owners/operators to meet emission limits, install emission control technologies, monitor emissions and/or operating parameters, and use specified work practices. In March 2005, EPA issued a *Revision of December 2000 Regulatory Finding,*[2] stating that the Agency no longer found it appropriate or necessary to regulate utilities under Section 112. This released the Agency from the requirement to regulate utilities using a MACT standard. EPA issued the finding the same day it issued CAMR, which established a mercury cap-and-trade program under Section 111.

For its *Revision of December 2000 Regulatory Finding*, EPA interpreted Section 112(n) to mean that utilities alone had to be the sole cause of a health hazard in order to be regulated under Section 112 and subject to MACT standards. Specifically, EPA developed the following "utility-attributable" hotspot definition for its revision: ". . . a waterbody that is a source of consumable fish with Methylmercury tissue concentrations, attributable solely to utilities, greater than EPA's Methylmercury water quality criterion of 0.3 milligrams per kilogram (mg/kg)."

EPA Response to Petitions for Reconsideration

Several State agencies and other organizations oppose EPA's adoption of a cap-and-trade program for mercury. These groups separately petitioned for reconsideration of the *Revision of December 2000 Regulatory Finding.* Among other things, they asserted that, in its analysis, EPA underestimated the impact of deposition resulting from local and regional sources and overestimated the impact of emissions from global sources. Thus, they argue, some mercury hotspots already exist, and requiring sources to comply with MACT standards would immediately reduce deposition in those areas. Further, these opponents to the cap-and-trade program believe the program could result in new mercury hotspots if some utilities bought excess emission credits instead of reducing emissions.

On October 21, 2005, EPA reopened for public comment certain aspects of its CAMR and, in a separate action, reopened for public comment certain aspects of its *Revision of December 2000 Regulatory Finding.* The action to reopen comment on CAMR was taken in response to petitions filed by 14 States, 5 environmental groups, a public utility, and a waste services association. The Agency stated that it agreed to reconsider several aspects regarding CAMR. The action to reopen comment on EPA's *Revision of December 2000 Regulatory Finding* was based on two petitions, one from 14 States and a second from 5 environmental groups and 4 Indian tribes. The Agency agreed to reconsider the legal issues underlying the decision as well as the methodology used to assess the

[2] *Revision of December 2000 Regulatory Finding on the Emissions of Hazardous Air Pollutants from Electric Utility Steam Generating Units and the Removal of Coal- and Oil-fired Electric Utility Steam Generating Units from the Section 112(c) List; Final Rule*, March 15, 2005.

amount of "utility-attributable" mercury levels in fish tissue and the public health implications of those levels. The Agency also agreed to reconsider how it defined a utility hotspot for the purposes of its finding concerning regulation of Utility Units under Clean Air Act Section 112. Comments regarding this reconsideration were accepted until December 19, 2005. The Agency was still evaluating comments at the time our field work ended.

Scope and Methodology

We conducted our review from September through December 2005, in accordance with *Government Auditing Standards* issued by the Comptroller General of the United States. We performed field work at EPA's Office of Air and Radiation in Washington, DC; the Office of Air and Radiation's Office of Air Quality Planning and Standards in Research Triangle Park, North Carolina; the Office of Research and Development in Research Triangle Park; and the Office of Water in Washington.

To answer our evaluation's objective, we examined: (1) the basis for the Agency's "utility-attributable" hotspot definition and the consistency of this definition with any prior Agency decisions regarding hotspots; (2) the key attributes, assumptions, and limitations of the models used to assess the impact of mercury emissions from coal-fired electric utility units under CAMR; and (3) the key variables used as inputs to the models as well as the basis for selecting these variables.

To gain an understanding of the definition of "utility-attributable" hotspots, the modeling and analyses EPA used to determine the potential for "utility-attributable" mercury hotspots after CAMR, and the inputs and assumptions associated with the Agency's analyses, we interviewed EPA staff involved in the development of CAMR or knowledgeable about the processes and models used in EPA's analyses. We also interviewed officials from State agencies and external organizations familiar with CAMR's development and EPA's hotspots analysis. We reviewed data and analyses developed in support of the rule, and selected public comments included in the rulemaking docket. We also reviewed related information provided by both EPA and non-EPA officials.

Our analysis focused on the key assumptions and limitations of the Community Multiscale Air Quality model, which was used to estimate mercury transport and deposition. We did not review in detail the assumptions, limitations, and uncertainties associated with the other models used in the Agency's analyses.

Appendix A provides additional details on scope and methodology.

Chapter 2
Monitoring Plan Needed to Address Uncertainties in EPA's Hotspots Analysis

As with any modeling assessment, uncertainties may exist. Uncertainties regarding EPA's analysis and conclusion that CAMR will not result in "utility-attributable" hotspots include:

- gaps in available data and science for mercury emissions estimates,
- limitations with the model used for predicting mercury deposition,
- uncertainty over how mercury reacts in the atmosphere, and
- uncertainty over how mercury changes to a more toxic form in waterbodies (i.e., methylation) and accumulates in fish tissue.

Two recent studies support the need for additional monitoring to ensure that EPA's hotspots analysis has properly estimated the contribution of local, regional, and global sources to U.S. deposition. These studies are:

(1) "*Mechanisms of Mercury Removal by O_3 and OH in the Atmosphere,*" Calvert, J.G., Lindberg, S.E., (published in *Atmospheric Environment*, Volume: 39, Number: 18, Page: 3355-3367), June 5, 2005, referred to in this report as the "Mechanisms of Mercury Removal Study;" and

(2) "*Sources of Mercury Wet Deposition in Eastern Ohio, USA,*" Keeler, G.J., et al., referred to in this report as the "Steubenville Study" (a peer review of the Steubenville Study was completed in December 2005 and the study was submitted for publication in a scientific journal in February 2006).

Results of both studies were not available until after EPA issued CAMR in March 2005, and thus could not have been considered in EPA's deliberations on CAMR. We believe the uncertainties associated with its CAMR analysis underscore the need for EPA to develop and implement a plan for monitoring the impact of CAMR on mercury deposition and mercury concentrations in fish tissue. Without implementation of a monitoring plan and/or improvements to current models, "utility-attributable" hotspots that can pose health risks may occur and go undetected.

EPA Analyzed Potential for "Utility-Attributable" Hotspots

In its *Revision of December 2000 Regulatory Finding,* EPA states it "does not believe that there will be any [utility-attributable] hot spots after implementation of CAIR [Clean Air Interstate Rule] and CAMR." EPA's analyses of mercury hotspots considered many factors that influence the way mercury is deposited to land and waterbodies. For its CAMR analysis, EPA used the Community

Multiscale Air Quality (CMAQ) model as the principal tool to predict patterns of mercury deposition and as an important part of assessing the potential for "utility-attributable" mercury hotspots under CAMR.

EPA considers the CMAQ to be the most capable model available for assessing the impacts of CAMR on mercury deposition within the United States. The model is designed to estimate pollutant concentrations and depositions over large areas, such as the continental United States. The model accounts for variations in mercury emissions, differences in the atmospheric reactions of mercury, and the impact of those factors on deposition.

However, there are important limitations associated with some of the inputs EPA used in CMAQ for its CAMR analysis. The July 2005 *Final Report: Second Peer Review of the CMAQ Model*, conducted by an independent panel that included State, academic, and private organizations, notes the following limitations:

> *CMAQ is a modeling system that simulates a wide range of physical, chemical and biological processes . . . Some of these processes are well understood, some reasonably well understood, and some only poorly understood. This wide range in the level of knowledge about the processes being modeled, and the fact that uncertainties in characterizing some of the processes correspond to areas of active research worldwide, means that some parts of the model code are sufficiently well established as to be considered fixed, while other parts of the code are under continuing development.*

Other models also played a role in EPA's analysis of the potential for hotspots under CAMR by contributing input data to CMAQ (see Appendix B for details on some of these other models). For example, a separate model was used to estimate the amount of mercury emissions from utilities based on certain economic assumptions, and another was used to predict weather patterns. Both the emissions and weather data were fed into CMAQ, and CMAQ predictions on deposition were fed into another model to estimate the effects of deposition on future mercury fish tissue concentrations.

In its hotspots analysis, the Agency discussed instances where conservative assumptions were used to avoid underestimating the impact of utilities. For example, in its hotspots analysis EPA did not screen out watersheds in which sources of mercury other than air deposition were significant. According to EPA, this may result in higher concentrations of methylmercury in fish being attributed to power plants than would be the case had EPA been able to account for non-air sources. In addition, EPA's hotspots analysis discusses the conservative estimates used in determining the oral reference dose for mercury (i.e., an estimate of the daily exposure to the human population, including sensitive subgroups, that is without an appreciable risk of deleterious effects during a lifetime). The reference dose and human exposure information were used to establish the water

quality criterion for methylmercury in fish tissue, the criterion used by EPA to represent a mercury hotspot.

Data and Science Gaps Exist for Mercury Emissions Estimates

While EPA has conducted activities to greatly increase its knowledge of mercury emissions from coal-fired utility plants, the Agency acknowledges that some uncertainty still exists when estimating total and speciated[3] mercury emissions and in projecting these emissions after implementation of various control technologies.

CMAQ requires the input of emissions inventory data to predict how emissions will transport and deposit. CMAQ was first run with a full emissions inventory to establish a base case scenario assuming the presence of all emissions. Next, CMAQ was run with emissions from coal-fired utilities removed, in what is called a "zero-out" run, to determine the impact of the variable that was zeroed out. EPA used this zero-out method to determine that no "utility-attributable" hotspots would occur after accounting for emissions reductions expected to be achieved from the Clean Air Interstate Rule and CAMR.

The utility emissions input into CMAQ were developed from the Integrated Planning Model (IPM). The IPM is a model of the U.S. electric power sector that can be used to evaluate the cost and emissions impacts of proposed policies to limit emissions of pollutants, including mercury. EPA has used the IPM in rulemakings since the mid 1990's. As part of that process, EPA takes comments on the underlying assumptions of the model and makes changes as a result. For its Clean Air Interstate Rule and CAMR analyses, EPA used IPM to estimate base case and future year national inventories of unit-specific mercury emissions under different control scenarios.

IPM uses equations (emission modification factors) to estimate utility emissions given the chemical composition of the coal being burned as well as various operating characteristics of the utility unit (e.g., type of control technology installed). These equations were based on various coal composition and emissions testing data collected during a 1999 Information Collection Request and more recent testing conducted by EPA, the Department of Energy, and industry participants.

While extensive data have been collected on mercury emissions from coal-fired utilities, some data and science gaps still exist with respect to understanding the effectiveness of specific controls in reducing mercury emissions from coal. As noted in the EPA Office of Research and Development's February 18, 2005,

[3] Mercury speciates into three basic forms: elemental, ionic, and particulate. Estimating the amount of speciated mercury emissions is important since the type of mercury emitted impacts how effectively it is captured by control technologies, and how it will react when emitted into the atmosphere. Differences in atmospheric reactions impact the amount and location of the mercury's deposition.

update of its study on control of mercury emissions, data and science gaps exist with respect to existing controls that are intended to reduce emissions of other pollutants with the co-benefit of reducing mercury, as well as emerging technologies specifically designed to reduce mercury emissions. The impact of these uncertainties on EPA's estimates of mercury emissions in base case and future years is qualitatively discussed in Agency documents but has not been quantified. The uncertainties could impact the accuracy of the estimated utility emissions input into CMAQ and CMAQ's resulting deposition estimates.

CMAQ Model Uncertainties and Limitations

CMAQ is useful for predicting regional and national patterns of deposition, but it has limitations that need to be carefully considered when used for modeling small areas of localized deposition and, thus, identifying hotspots. When emissions data are fed into CMAQ, the model averages the data over an area known as a "grid cell." CMAQ can predict deposition results over grid cells of various sizes (or resolutions) as specified by the modeler.

For CMAQ, EPA used a 36 kilometer (km) grid resolution (36 km x 36 km) for its Clean Air Interstate Rule and CAMR modeling, which equates to a surface area approximately 22 miles wide by 22 miles long, or approximately 484 square miles. The model provides one average concentration for the entire area. For example, if there is only one power plant in the corner of a grid square, that plant's emissions are averaged over the entire 36 km x 36 km area. Averaging over grid cells may result in a smoothing out of areas of high and low deposition. EPA acknowledges this limitation in its *Effectiveness Technical Support Document:*[4]

> *CMAQ immediately dilute[s] simulated emissions into the entire grid volume in which they are released. This causes an artificially fast dilution and under-represents direct deposition from air to surfaces near emission sources . . .*

When looking for hotspots, the ability to identify areas of localized deposition is important. Using the CMAQ model at 36 km x 36 km, in the opinion of some EPA officials we interviewed, was too coarse a resolution to be able to pinpoint small areas of localized deposition. Some EPA officials stated that use of a finer resolution, such as 12 km grid size, is possible in CMAQ. However, at very fine resolutions – for instance, a 4 km grid size – the meteorological components of the model probably fall apart and may introduce greater uncertainties in model results. EPA outlines three reasons for using a 36 km grid square size in its *Effectiveness Technical Support Document*. First, the larger grid size would account for mercury deposition that enters a watershed through groundwater

[4] *Methodology to Generate Deposition, Fish Tissue Methylmercury Concentrations, and Exposures for Determining Effectiveness of Utility Emission Controls (Effectiveness Technical Support Document)*. U.S. EPA, March 15, 2005.

inflow and runoff, as opposed to a smaller grid size that may only account for direct inputs to surface water. Second, in larger waterbodies where there is substantial fishing activity, the fish species consumed by humans are likely migratory and the accumulation of mercury in these fish will come from deposition over a larger area. Third, many anglers may catch fish from a variety of waterbodies in a watershed, thus a larger grid size would account for this fishing pattern.

Study Finds Different Rates of Atmospheric Chemical Reactions

The Mechanisms of Mercury Removal Study developed information on the rates of atmospheric chemical reactions involving mercury that is different than rates used by EPA in its CAMR hotspots analysis. The study was published in June 2005 after EPA issued CAMR. Rate constants, which quantify the speed or rate of chemical reactions, are the most important inputs affecting modeling results. The accuracy of rate constants can affect the accuracy of modeling results. Oxidation is an atmospheric process that makes mercury more reactive and is the most important reaction associated with mercury deposition. The mercury oxidation rate affects how quickly mercury is deposited and influences its properties and behavior. For example, oxidation makes elemental mercury more water soluble and more quickly deposited; if mercury emitted from a source comes out already oxidized, it can be immediately deposited near the source (depending on meteorological conditions and other factors).

Results of the Mechanisms of Mercury Removal Study regarding mercury reactions and associated rates suggest that emissions from global sources potentially account for less mercury deposition in the United States than previously believed. This means that the contribution of global sources to U.S. deposition may have been overestimated in EPA's analysis and the impact from domestic sources underestimated. According to the Agency scientist responsible for developing mercury capabilities in CMAQ, if the study's results about rate constants are accurate, then chemical formulations currently used in all other atmospheric simulation models, including CMAQ, could be incorrect (when modeling mercury deposition).

Uncertainties Noted with Methylation and Bioaccumulation

Assumptions about methylation and bioaccumulation directly impact the resulting predictions about mercury fish tissue concentrations after implementation of CAMR. Mercury methylation is a complex process that occurs in the environment when oxidized mercury is transformed into highly toxic methylmercury, which bioaccumulates (builds up) in fish tissue. Some of the important factors affecting methylation rates and bioaccumulation were not fully accounted for in EPA's analysis. Also, a lack of knowledge about some factors used in EPA's analysis is a source of uncertainty in EPA's conclusions about mercury fish tissue concentrations.

Methylation. Transformation of mercury to methylmercury occurs at varying speeds in different waterbodies, and EPA's analysis did not fully account for this variation. Methylation occurs when mercury enters waterbodies and bacteria transform it to methylmercury, a highly toxic and bioaccumulative form of mercury. Methylation of mercury occurs in waterbodies at highly variable speeds depending on various ecosystem-specific factors, including: the bacteria in the waterbody, the type of land surrounding the waterbody, the quantity of certain substances such as sulfate and carbon in the waterbody, and the pH (chemistry) of the waterbody. Thus, two adjacent waterbodies with equal mercury deposition can have different concentrations of mercury in fish.

EPA's analysis did not address individual differences between waterbodies, or the time it takes for different waterbodies to adjust to changes in atmospheric deposition. The modeling assumed that the environmental factors affecting the formation of methylmercury remain constant. EPA acknowledges that a lack of knowledge about methylation is "a major contributor to overall uncertainty" in its analysis; however, the effect of this uncertainty on the Agency's ability to inform mercury control policies is highly variable. An EPA official stated that variance in methylation rates was taken into account because actual methylmercury fish tissue measurements, which reflect varying methylation rates among different waterbodies where measurements were obtained, were used in the "utility-attributable" hotspot analysis. As explained in the next section, we found that concerns remain about these fish tissue measurements, which call into question how well they address methylation uncertainties.

Bioaccumulation. EPA's analysis did not fully account for the highly variable ways that mercury bioaccumulates in fish. When mercury deposition to a waterbody changes because of reductions in emissions, it can take time for those changes to be reflected in fish tissue methylmercury concentrations. Fish absorb methylmercury from their food and directly from water as it passes over their gills. To predict levels of methylmercury in fish tissue, CMAQ deposition results for a given area were input into a model that assumed a proportional relationship between declines in atmospheric mercury deposition and declines in mercury fish tissue concentrations. For example, a 50-percent decrease in mercury deposition rates was projected to lead to a 50-percent decrease in mercury concentrations in fish. However, drawing conclusions and making comparisons between different fish types is limited in that mercury bioaccumulates in highly variable ways among fish, both between species and within individual fish of a species. To establish a 2001 baseline estimate of methylmercury fish tissue concentrations, EPA used data from the National Listing of Fish Advisories and the National Lake Fish Tissue Survey:

> *For included locations, samples for the same species are averaged across all available years (post 1998), and then the highest averaged per species concentration is used to represent the methylmercury concentration for that*

sample location. For example, if there are two species at a location, walleye and pike, with three sampling dates for each species, we would first average over the three sample dates for each species, and then select walleye if the average for walleye is highest, or select pike if the average for pike is highest. . . . Assignment of the maximum average species concentration recognizes the greater risk to an individual consuming species with higher accumulation of mercury while respecting the fact that each sample for an individual species is only an estimate of the true mean concentration in that species.

According to EPA staff, the adequacy of current fish tissue data is sparse – it is patchy, non-standardized from State to State, and only identifies potential problems where data were actually collected. Regarding EPA's fish tissue data, an Agency official said, "The data does not support the conclusion that CAMR will not cause hotspots." In its *Effectiveness Technical Support Document*, EPA states that, among other limitations, the model it used to estimate changes in methylmercury fish tissue concentrations does not account for the time lag between a reduction in mercury deposition and a reduction in methylmercury concentrations in fish tissue. However, the document stated that EPA is unaware of any other tool for performing a national-scale assessment of the change in fish methylmercury concentrations resulting from reductions in atmospheric deposition of mercury.

Study Shows Significant Deposition from Local Sources

Results from the Steubenville Study,[5] a multiyear study in the Ohio River Valley, found that approximately 70 percent of mercury wet deposition at Steubenville, Ohio in 2003 and 2004 was attributable to local/regional coal combustion sources, predominantly from utility boilers.[6] The results of the Steubenville Study suggest that additional monitoring is necessary to ensure that EPA's CAMR analysis has properly estimated the contribution of local and regional mercury deposition. For example, while CMAQ results do not provide an estimate of mercury wet deposition for Steubenville specifically (due to its 36 km x 36 km grid cell area), it estimated for 2001 that 44 percent of the wet deposition in the grid cell containing Steubenville was from coal-fired utilities. Spatial and temporal differences[7] between the Steubenville Study and EPA's CAMR analysis do not allow for their results to be fully comparable; however, data from other monitoring sites further suggest that monitoring is needed to ensure that CMAQ

[5] A peer review of the Steubenville Study was completed in late December 2005 and it was submitted for publication in a scientific journal in February 2006.

[6] The Steubenville Study results have an uncertainty bound of approximately 15 percent. This uncertainty bound does not follow a normal distribution pattern but is positively skewed, i.e., the upper bound of the 95 percent confidence interval extends further from the estimate than the lower bound.

[7] The Steubenville Study wet deposition results are for 2003 and 2004 and (1) represent the wet deposition for a specific monitoring location; (2) include wet deposition for all coal-combustion sources; and (3) have quantified estimates of uncertainty. Conversely, the CMAQ results are for the year 2001 and (1) represent an estimate for a much larger area (i.e., a 36 km x 36 km grid cell); (2) represent deposition from coal-fired utilities only; and (3) do not quantify uncertainty.

has not underestimated wet deposition in some locations. An Agency scientist noted that:

> *. . .CMAQ runs conducted using 2001 emissions data for CAMR modeling showed that there are areas in the U.S. where domestic sources create large areas of enhanced deposition (e.g., up to 60% of wet mercury deposition in some areas originated from domestic coal combustion sources). The Steubenville measurements are consistent with these projections. As an example of uncertainties related to CMAQ . . . the University of Michigan has run a network of event-based mercury monitoring sites in the Midwest and Vermont and the 2001 CMAQ model runs systematically underestimate the deposition observed at these sites (in some cases by over a factor of 2).*

Senior Office of Air and Radiation officials told us that the Steubenville area is known to have higher-than-average deposition from coal-fired utilities, and that the preliminary monitoring results were not unexpected. OAQPS noted that for grid cells neighboring the Steubenville grid cell, the CMAQ model predicted that a higher percentage of mercury deposition was attributable to utility coal combustion (i.e., 57 to 71 percent). Preliminary results of the Steubenville Study were made available to Agency officials shortly after EPA's promulgation of CAMR and the *Revision of December 2000 Regulatory Finding* in March 2005, but were not available for consideration by the Agency during its promulgation of these rules. The Agency noted that they analyzed a number of scientific studies in developing CMAQ, but our evaluation did not consider all of the scientific evidence EPA used in developing CMAQ. As noted in Appendix A, we did not evaluate all the inputs and assumptions associated with EPA's mercury hotspots analysis. Additional limitations of our evaluation are listed in Appendix A.

Uncertainties Underscore Need for Mercury Monitoring Plan

In the preamble to the *Revision of December 2000 Regulatory Finding*, EPA stated that although it believed the likelihood of a "utility-attributable" hotspot occurring to be "remote," it intended to closely monitor the potential for hotspots, continue to advance the state of the science of mercury fate and transport, and take appropriate action if the possibility of a "utility-attributable" hotspot arose after implementation of CAMR. However, at the time we completed our field work, EPA had not yet developed a plan for monitoring hotspots. Given the uncertainties associated with the inputs to the CMAQ model and the results of recent studies as noted, it is important for EPA to have a plan to monitor mercury deposition. Mercury monitoring data could assist the Agency in determining "utility-attributable" hotspots, and in evaluating and improving the accuracy of its mercury fate and transport models. Without a mercury monitoring plan, "utility-attributable" hotspots could potentially occur after implementation of CAMR but be less likely to be identified due to a lack of deposition data or reliable modeling techniques to identify mercury sources.

Field measurement of mercury deposition could improve EPA's ability to conduct source apportionment studies to help to determine whether a hotspot was "utility-attributable." To assess whether CAMR results in "utility-attributable" hotspots, EPA must have mercury deposition data that enable it to identify the mercury source. Source-apportionment studies, such as that conducted by EPA in Steubenville, are designed to accomplish this task. Such studies estimate a source's contribution to mercury deposition and require the collection of deposition samples and measurements of trace elements in addition to mercury. Trace elements are elements that are co-emitted with mercury from particular sources, and help identify from which source(s) the deposited mercury originally came. For example, sulfur and selenium are trace elements associated with coal combustion. When these elements are in samples of deposited mercury, they indicate the mercury came from coal combustion sources. By employing a monitoring plan that incorporates more studies of this nature, EPA can better assess the impact that utilities have on mercury deposition and resulting fish tissue concentrations.

Mercury deposition data would also help EPA improve its current understanding of mercury fate and transport, and allow the Agency to validate and improve mercury deposition estimation models and techniques. Model performance can be assessed by comparing model predictions to actual field data. While mercury deposition data are available through the Mercury Deposition Network (MDN), these data have important limitations for model evaluation, particularly modeling designed to identify mercury hotspots:

- The MDN measures only wet deposition because there is no adequate field methodology currently available for dry deposition.

- The MDN does not generally provide deposition monitoring data for areas expected to be of greatest concern for deposition from local emissions sources. This is because MDN monitoring sites are generally located in rural locations that do not have local sources of emissions.

- There are large areas of the nation with few or no MDN monitoring sites.

- The MDN collects deposition samples on a weekly basis, so it does not accurately measure the impacts of individual events, such as rain or snowfall.

- The MDN sites do not collect trace element data, such as sulfur and selenium data for coal combustion, which is needed to conduct source apportionment modeling.

Due to the limitations associated with available data from the current mercury deposition monitoring network, EPA is currently unable to fully assess the accuracy of CMAQ's mercury deposition predictions against actual field

measurements. Agency officials told us that the EPA Office of Research and Development's National Exposure Research Laboratory was already implementing a research plan for mercury monitoring, but recent budget reductions have halted the program.

Conclusion

EPA has acknowledged uncertainties and limitations in its analysis of the potential for "utility-attributable" hotspots. The results from two studies – the Mechanisms of Mercury Removal Study and the Steubenville Study – illustrate uncertainties about some of the key assumptions used in CMAQ and the deposition results projected by the model. Further consideration of uncertainties could alter EPA's conclusions about the potential for "utility-attributable" mercury hotspots. EPA indicated it will closely monitor hotspots, continue to advance mercury science, and take appropriate actions if hotspots arose. To accomplish this, the Agency needs to establish a monitoring plan to conduct source-apportionment studies to measure the impact of CAMR and to assist in evaluating the accuracy of its model predictions against actual field data.

Recommendation

We recommend that the Acting Assistant Administrator for Air and Radiation:

2-1 Work with the Assistant Administrator for the Office of Research and Development to develop and implement a mercury monitoring plan, including milestones and responsible program offices for implementing each component of the plan, to: (1) assess the impact of CAMR, if adopted, on mercury deposition and fish tissue; and (2) evaluate and refine, as necessary, mercury estimation tools and models. This effort should consider the suitability of the Office of Research and Development's mercury research plan for addressing these objectives.

Agency Comments and OIG Evaluation

The Agency generally agreed with the recommendation in Chapter 2 of the report. However, the Agency expressed concern with our characterization of some scientific issues in the report and offered clarification on three specific issues. We accepted the Agency's technical clarifications and have made changes to the final report as appropriate. The Agency also provided us with additional concerns not specifically addressed in its written response to our draft report. We met with the Agency to discuss these concerns, and made changes to the final report as appropriate. In response to our recommendation, the Agency stated that the Office of Air and Radiation and Office of Research and Development will continue to work together to ensure that they are using the best possible information to assess the transport, transformation, deposition, and fate of mercury emissions in the United States. We support the Agency's commitment to

using the best possible information to assess the impact of mercury emissions in the United States, and continue to recommend the Agency develop a monitoring plan to better ensure that this happens. The Agency's formal written response is in Appendix C.

Chapter 3
EPA Needs to Clarify Conditions Under Which CAMR Performance Standards Can be Tightened

EPA does not clearly explain how the "utility-attributable" hotspot definition affects the Agency's ability to revise performance standards under CAMR. When CAMR is read in conjunction with the *Revision of December 2000 Regulatory Finding,* we believe the CAMR could be interpreted to preclude EPA from taking action to mitigate a mercury hotspot (such as tightening the cap or utilities' performance standards) unless it first determined that the hotspot was solely "utility-attributable." If this were the case, such a prerequisite could limit EPA's ability to reduce methylmercury fish tissue concentrations below acceptable levels, and thus address public health hazards that are being caused predominantly (but not "solely") by utilities. This could also impact EPA's ability to reduce the number of waterbodies with fish consumption advisories.

EPA Provides "Utility-Attributable" Hotspot Definition

In its *Revision of December 2000 Regulatory Finding,* EPA defined a "utility-attributable" hotspot[8] as:

> *". . . a waterbody that is a source of consumable fish with Methylmercury tissue concentrations, attributable solely to utilities, greater than the EPA's Methylmercury water quality criterion of 0.3 mg/kg."*

This definition only considers the contribution of one source (utilities) on environmental problems that could threaten human health, and would only consider a hotspot to be "utility-attributable" if the utility emissions alone caused methylmercury in fish tissue to exceed 0.3 mg/kg.

According to the preamble of the *Revision of December 2000 Regulatory Finding,* EPA adopted this definition based on its interpretation of Clean Air Act Section 112(n), which directed the Agency to ". . . study hazards to public health reasonably anticipated to occur as a result of emissions by electric utility steam generating units." EPA interpreted the language "as a result of" to mean that utility emissions must be the *sole* cause of a health hazard, and not just contribute to causing a hazard, to be regulated under Section 112. Using EPA's methylmercury water quality criterion of 0.3 mg/kg in fish tissue as the one

[8] EPA uses the terms "hotspot," "hot spot," "utility hot spot," and "utility-attributable hotspot" interchangeably throughout the *Revision of December 2000 Regulatory Finding* when referring to a waterbody that is a source of consumable fish with methylmercury tissue concentrations, attributable solely to utilities, greater than the EPA's methylmercury water quality criterion of 0.3 mg/kg.

measure for "hazards to public health," EPA adopted the "utility-attributable" hotspots definition to determine whether such utility hotspots would remain after implementation of the Clean Air Interstate Rule and CAMR. Based on the analysis described in Chapter 2 of this report, EPA stated that it did not believe that "utility-attributable" mercury hotspots would exist after implementing these rules, therefore supporting the Agency's decision that utilities did not need to be regulated under Section 112 of the Clean Air Act.

"Utility-Attributable" Definition Could be Interpreted to Limit EPA's Ability to Mitigate Hotspots

The "utility-attributable" definition could be interpreted to limit EPA's ability to address waterbodies with elevated levels of mercury unless utility emissions were the sole cause of the problem. This could in turn limit EPA's ability to reduce the number of waterbodies with fish consumption advisories where there is a health risk due to the combined impact of mercury from all sources, including air emissions.

As discussed in its December 1997 *Mercury Study Report to Congress*, EPA stated that there is "clearly" a need to address the combined impacts of mercury originating from all sources, including air emissions, wherever the combination of sources have been related to unacceptably high mercury levels in fish. Further, in its *December 2000 Finding,* EPA recognized concerns about the potential local impact of mercury trading programs and acknowledged that:

> *. . . approaches that involve economic incentives must be constructed in a way that assures that communities near the sources of emissions are adequately protected.*

Within CAMR and the *Revision of December 2000 Regulatory Finding*, EPA specifies several actions it might take to mitigate the effects of a hotspot in the event one should be identified. However, our analysis of the revision and CAMR suggests that the Agency may be precluded from taking any of those actions unless the hotspot first meets the criteria of a "utility-attributable" hotspot. EPA officials told us that this was not the intent of the rule, but agreed that the rule could be clearer.

CAMR and Revision Must be Read Together

Based on our reading of CAMR and the *Revision of December 2000 Regulatory Finding,* we conclude that the definition of a hotspot presented in the revision is intended to apply to CAMR. CAMR and the revision were issued on the same day and address the same subject matter. In addition, the preamble to the CAMR restates EPA's conclusion from the revision, but refers to it as part of "this action":

As stated elsewhere in this action EPA does not believe that utility-attributable hot spots will be an issue after implementation of CAIR [Clean Air Interstate Rule] and CAMR.

Because "utility-attributable" hotspots are not discussed "elsewhere" within CAMR, we conclude that "this action" refers to the other, closely related action published by EPA on the same day. This action, the *Revision of December 2000 Regulatory Finding*, defines "utility-attributable" hotspots and also explains that EPA may address hotspots under "other authorities under the CAA [Clean Air Act]," should they occur. However, the only mechanism to which EPA refers in order to addresses potential future hotspots – and the only mechanism presently promulgated – is CAMR. The revision cites the following ways it could address "utility-attributable" hotspots:

. . . if in the future we determine that utility-attributable hotspots exist and that those hotspots occur as the result of Hg emissions from coal-fired Utility Units, we may promulgate a tighter section 111 standard of performance, provided we determine the technology can achieve the contemplated reductions. We could revise the standard of performance by adjusting the cap-and-trade program to limit trading by high-emitting Utility Units. . . . Thus, although we cannot conclude today which statutory authority we would implement to address utility attributable hotspots because that determination necessarily hinges on the facts associated with the identified hotspots, we do conclude that were such a situation to occur, we believe that EPA has adequate authority to address any such situation that may arise in the future.

When read together, these regulatory actions suggest that a finding of a solely "utility-attributable" mercury hotspot is necessary to initiate Agency action to mitigate hotspots under CAMR. If this were the case, EPA would be precluded from requiring additional mercury reductions from the utility industry, even if it were determined that utilities were significantly contributing to a hotspot, if the utilities were not the sole cause of the hotspot. For example, if methylmercury fish tissue concentrations for a waterbody were at 0.32 mg/kg, EPA's water quality criterion of 0.3 mg/kg would be exceeded. If, in this hypothetical case, utility mercury emissions were causing 0.3 mg/kg or less of the total methylmercury, under the requirement as written, utilities would be excluded from any additional reductions to help mitigate the problem.

We discussed our interpretation with Office of Air and Radiation officials. These officials confirmed that the "utility-attributable" hotspot definition in the revision applies to the CAMR. However, these officials told us that this definition does not establish a criterion for when the Agency can adjust the performance standards under CAMR. They noted that under Section 111, performance standards are to be reviewed every 8 years, and can be adjusted for various reasons.

Conclusion

The two rules related to controlling mercury emissions from coal-fired utilities were issued on the same day and refer to and are consistent with each other. Thus, it appears that they are intended to be read together. Further, the "utility-attributable" definition in the *Revision of December 2000 Regulatory Finding* applies to the discussion of hotspots in CAMR, and this definition establishes a criterion for when the CAMR can be adjusted to address a potential health hazard. If this were the case, tighter performance standards for utilities contributing to a hotspot could not be promulgated unless it was first determined that the hotspot was solely "utility-attributable." Although not the intent of the rulemaking, EPA officials agreed that the rule could be clearer. We believe CAMR, if adopted, should be clarified to avoid any possible misinterpretation of how the "utility-attributable" definition affects EPA's ability to modify utility performance standards.

Recommendation

If EPA decides to adopt CAMR after the rule reconsideration process, to better ensure protection of public health and the environment, we recommend that the Acting Assistant Administrator for Air and Radiation:

3-1 Explain in CAMR that the "utility-attributable" hotspot definition found in the revision does not establish a prerequisite for making future changes to the performance standards under CAMR.

Agency Comments and OIG Evaluation

The Agency's response did not specifically address our analysis and conclusion that CAMR could be interpreted to use the "utility-attributable" hotspot definition as a prerequisite for future changes to CAMR. The Agency commented that, while information regarding "utility-attributable" hotspots would be relevant to future possible revisions to CAMR, such hotspots are not a prerequisite to the Agency making changes to performance standards under CAMR. We believe the Agency's intent should be made clear in the final rule. Accordingly, we revised our final report to recommend that EPA, to better ensure protection of public health and the environment, explain in the CAMR that the "utility-attributable" hotspot definition set forth in the revision is not a prerequisite for making changes to the CAMR. After submitting its formal written response to the draft report the Agency also suggested clarifying language to parts of Chapter 3. We accepted some of the suggestions and incorporated them into the final report. The Agency's formal written response is in Appendix C.

Appendix A

Details on Scope and Methodology

We conducted interviews with staff from the following EPA offices:

- Office of Air and Radiation, including its Office of Air Quality Planning and Standards and Office of Atmospheric Programs.
- Office of Research and Development, including its National Exposure Research Laboratory and National Center for Environmental Research.
- Office of Policy, Economics, and Innovation.
- Office of Water.

We also interviewed officials from the following external organizations: the National Oceanic and Atmospheric Administration, including its Air Research Laboratory; the Northeast States for Coordinated Air Use Management; and the Clean Air Task Force.

To understand the variables associated with mercury fate and transport modeling and, specifically, CMAQ, we reviewed and/or discussed with the above officials selected reports and studies, including:

- Mechanisms of Mercury Removal by O_3 and OH in the Atmosphere. Calvert Jack G.; Lindberg Steve E. *Atmospheric Environment*, Volume: 39, Number: 18, Page: 3355-3367, June 5, 2005.
- The National Oceanic and Atmospheric Administration's September 2005 (draft) report by Cohen, et al, *Report to Congress: Mercury Contamination in the Great Lakes*.
- EPA's *Regulatory Impact Analysis of the Final Clean Air Mercury Rule*, March 2005.
- EPA's *Mercury Study Report to Congress*, December 1997.
- A slide presentation on EPA's Steubenville, Ohio, study, *Preliminary Results from Steubenville Hg Deposition Source Apportionment Study*, April 27, 2005.
- The most recent peer review of CMAQ, *Final Report: Second Review of the CMAQ Model*.
- *Technical Support Document: Methodology Used to Generate Deposition, Fish Tissue Methylmercury Concentrations, and Exposure for Determining Effectiveness of Utility Emission Controls. Analysis of Mercury from Electricity Generating Units*, March 17, 2005 (revised).
- *Technical Support Document for the Final Clean Air Mercury Rule: Air Quality Modeling*, March 2005.
- *Emissions Inventory and Emissions Processing for the Clean Air Mercury Rule*, March 2005.

To gain an understanding of State and environmental groups' concerns related to EPA's analysis of potential "utility-attributable" hotspots under CAMR, we reviewed the following selected comments:

- The December 19, 2005 comments submitted *In Reconsideration of: Revision of December 2000 Regulatory Finding on the Emissions of Hazardous Air Pollutants From Electric Utility Steam Generating Units and the Removal of Coal- and Oil-Fired Electric Utility Steam Generating Units from the Section 112(c) List 70 Fed. Reg. 62200 (Oct. 28, 2005); and Standards of Performance for New and Existing Stationary Sources: Electric Utility Steam Generating Units 70 Fed. Reg. 62213 (Oct. 28, 2005). Comments Submitted by: The States of New Jersey, California, Connecticut, Delaware, Illinois, Maine, Massachusetts, Minnesota, New Hampshire, New Mexico, New York, Pennsylvania, Rhode Island, Vermont, and Wisconsin*, Docket No. OAR-2002-0056.

- The December 19, 2005 comments submitted regarding the *"Revision of December 2000 Regulatory Finding on the Emissions of Hazardous Air Pollutants From Electric Utility Steam Generating Units and the Removal of Coal- and Oil-Fired Electric Utility Steam Generating Units From the Section 112(c) List: Reconsideration," 70 Fed. Reg. 62,200 (October 28, 2005). Comments of: Clean Air Task Force, Izaak Walton League of America, Natural Resources Council of Maine, Ohio Environmental Council, U.S. Public Interest Research Group, Natural Resources Defense Council, Chesapeake Bay Foundation, Waterkeeper, Aroostook Band of Micmac Indians, Houlton Band of Maliseet Indians, Penobscot Indian Nation, The Passamaquoddy Tribe at Indian Township.*

To gain an understanding of EPA's definition of "utility-attributable" hotspots and the basis for that definition, we reviewed the following regulatory actions:

- *Regulatory Finding on the Emissions of Hazardous Air Pollutants From Electric Utility Steam Generating Units*, December 20, 2000.
- *Proposed National Emission Standards for Hazardous Air Pollutants; and, in the Alternative, Proposed Standards of Performance for New and Existing Stationary Sources: Electric Utility Stream Generating Units; Proposed Rule*, January 30, 2004.
- Final Rule – Preamble - *Standards of Performance for New and Existing Stationary Sources: Electric Utility Steam Generating Units*, March 15, 2005.
- Final Rule – Regulatory Text - *Standards of Performance for New and Existing Stationary Sources: Electric Utility Steam Generating Units*, March 15, 2005.
- Final Rule - *Revision of December 2000 Regulatory Finding on the Emissions of Hazardous Air Pollutants from Electric Utility Steam Generating Units and the Removal of Coal- and Oil-fired Electric Utility Steam Generating Units from the Section 112 (c) List*, March 15, 2005.
- *Reconsideration: Revision of December 2000 Regulatory Finding on the Emissions of Hazardous Air Pollutants from Electric Utility Steam Generating Units and the Removal of Coal- and Oil-fired Electric Utility Steam Generating Units from the Section 112 (c) List*, October 21, 2005.
- *Reconsideration: Standards of Performance for New and Existing Stationary Sources: Electric Utility Steam Generating Units*, October 21, 2005.

Prior Coverage

In a prior EPA OIG report, *Additional Analyses of Mercury Emissions Needed Before EPA Finalizes Rules for Coal-Fired Electric Utilities* (2005-P-00003), dated February 3, 2005, we cited concerns about EPA's limited assessment of the potential for mercury hotspots resulting from its (then proposed) cap-and-trade program under CAMR. In that report, we recommended that EPA further assess the risk of hotspots and, if necessary, identify how the Agency would reassess the hotspot issue. In response to our recommendation, EPA stated that it did not believe utility emissions would result in hotspots based on additional analyses it had performed, particularly after implementation of the Clean Air Interstate Rule and CAMR, but it would monitor the situation and take action if necessary. For this current review, we evaluated EPA's analysis of hotspots, its conclusion that there will be no "utility-attributable" hotspots after implementation of the Clean Air Interstate Rule and CAMR, and plans the Agency may have in place to continue to monitor the issue. Details on what we found, including recommendations, are in Chapters 2 and 3 of this current report.

Internal Controls

Government Auditing Standards require that auditors obtain an understanding of internal control significant to the audit objectives and consider whether specific internal control procedures have been properly designed and placed in operation. This evaluation was a limited-scope assessment of certain analyses pertaining to a rulemaking. Thus, we determined whether the Agency's hotspots analysis and conclusions were peer reviewed, and if the key model used in this analysis was separately peer reviewed. Peer review is a key internal control for ensuring the acceptability of scientific data and processes. We found that CMAQ, the main model used by EPA in its hotspots analysis, was peer reviewed; however, we found no evidence that the Agency's overall hotspots analysis, described in the document *Methodology to Generate Deposition, Fish Tissue Methylmercury Concentrations, and Exposures for Determining Effectiveness of Utility Emission Controls,* was peer reviewed. The Agency's *Ecosystem Scale Modeling for Mercury Benefits Analysis*, part of the Regulatory Impact Analysis for the CAMR, was peer reviewed. The benefits analysis was similar to the hotspots analysis, but it assessed the impact of CAMR on a national scale, as opposed to identifying localized hotspots or local-scale impacts.

Limitations

Our work had several limitations. Specifically, we did not:

- Review every model that contributed to EPA's analysis of the potential for "utility-attributable" hotspots under CAMR.
- Evaluate all of the inputs and assumptions associated with EPA's mercury hotspots analysis.
- Evaluate the adequacy of EPA's water quality criterion to protect human health.

Models Used in CAMR Analysis

The following diagram depicts how data from each model were used in EPA's hotspot analysis. Details on each model follow the diagram.

```
        MM5
         ↓
IPM → CMAQ → MMaps ≈ Changes in methylmercury levels in fish tissue
         ↑
    GEOS-CHEM
```

Model	Purpose	Contribution to Hotspot Analysis
Integrated Planning Model (IPM)	• To analyze future cost and emissions impacts of proposed environmental regulations upon utilities.	Estimates mercury emissions from utilities after implementation of Clean Air Interstate Rule and CAMR.
Mesoscale Model (MM5)	• To provide meteorological information, such as wind, temperature, precipitation, and sea level pressure.	Simulates weather patterns, which affect where mercury deposits.
Goddard Earth Observing System-CHEMistry (GEOS-CHEM) Global Model	• To provide a global three-dimensional model of atmospheric chemistry driven by meteorology.	Uses global chemistry and transport information to provide global/background mercury concentrations.
Community Multiscale Air Quality (CMAQ) Model	• To estimate mercury deposition. • To simulate various chemical and physical processes thought to be important in the atmospheric transformation and distribution of mercury.	Estimates amount of mercury deposition occuring within 36 km^2 grid cells after implementation of Clean Air Interstate Rule and CAMR.
Mercury Maps (MMaps)	• To relate changes in mercury air deposition rates to changes in mercury fish tissue concentrations on a national scale.	Uses CMAQ deposition data to estimate fish tissue concentrations of methylmercury based on the assumption of a 1-to-1 ratio between reductions in air deposition and reductions in average methylmercury fish tissue concentrations.

Agency Response to Draft Report

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

Bill Roderick, Acting Inspector General
Office of the Inspector General
Office of Program Evaluation
1301 Constitution Ave. NW (2400 T)
EPA West Building
Washington, DC 20004

Dear Mr. Roderick:

Thank you for the opportunity to comment on the draft Office of the Inspector General (OIG) report entitled ***"Monitoring Needed to Assess Impact of EPA's Clean Air Mercury Rule on Potential Hotspots."*** In reviewing the draft report, we acknowledge your acceptance of the majority of the issues we identified in our earlier review. We have also recently supplied your office with additional written comments pertaining to the modeling analyses associated with the Steubenville project. We believe that the collective scientific and engineering expertise within EPA's Offices of Air and Radiation (OAR) and Research and Development (ORD) puts our offices in a unique position to assess the current state-of-the-science with respect to mercury transport, deposition, and fate, and its impact on the creation of utility-attributable hotspots.

We continue to have concerns about the portrayal of some scientific issues in the report, and note three areas where we would like to provide clarifying remarks. First, with respect to the potential changes in the atmospheric reaction rates within the Community Multiscale Air Quality (CMAQ) model (see pages 9 and 10), such changes would be made uniformly in **all** mercury transport/deposition models, not just CMAQ. Thus, the enhancements would create different results in any assessment using these numerical simulation technologies. Second, regarding our need to improve ambient monitoring (see page 13), the report should acknowledge that the Mercury Deposition Network (MDN) currently measures only wet deposition because there is no adequate field methodology available for dry deposition.

Finally, in terms of how EPA addressed the uncertainties in methylation and bioaccumulation rates between different fresh water bodies, our supporting health benefits assessment materials describe in great detail our complete understanding of these processes. You are correct to point out, and we clearly acknowledge in our documents, the uncertainties associated with mercury transport, deposition, and effects. At the same time, it should be acknowledged that the magnitude of uncertainties and their effect on our ability to inform mercury control policies is highly variable. We believe we have clearly explained the science and the uncertainties and provided a solid foundation for the Clean Air Mercury Rule (CAMR).

In your draft report, you recommend two specific follow-up actions for the Agency. Below we address each of these recommendations.

Recommendation 2-1: ***Work with the Assistant Administrator for the Office of Research and Development to develop and implement a mercury monitoring plan, including milestones and responsible program offices for implementing each component of the plan, to: (1) assess the impact of CAMR, if adopted, on mercury deposition and fish tissue, and, (2) evaluate and refine, as necessary, mercury estimation tools and models. This effort should consider the suitability of the Office of Research and Development's mercury research plan for addressing these objectives.***

EPA currently operates the MDN, which is located predominantly in the eastern U.S. and monitors only wet deposition. In the technical support documents supporting CAMR, EPA has continually highlighted the need for and the willingness to support additional ambient monitoring, including the development of dry deposition monitoring, to enhance our ability to assess the numerical accuracy of our sophisticated simulation tools – e.g., the CMAQ model. As you are aware, ORD has been heavily involved over the past decade in developing the CMAQ model, and is actively engaged in utilizing ambient data and the latest scientific information to update the model to reflect the best possible chemistry and physics. OAR and ORD will continue to work together to ensure that we are using the best possible information to assess the transport, transformation, deposition, and fate of mercury emissions in the U.S.

Recommendation 3-1: ***If EPA decides to adopt CAMR after the rule reconsideration process, we recommend that the Acting Assistant Administrator for Air and Radiation: Specifically explain what role the "utility-attributable" hotspot definition has in determining whether to make any future changes to the performance standards under CAMR.***

EPA has explained to your staff that while information regarding utility-attributable hotspots would be relevant to future possible revisions to CAMR, such hotspots are not a prerequisite. CAMR controls are based on the new source performance standards (NSPS) as set forth in section 111 of the Clean Air Act. To this end, the Agency is required by law to review and revise, as necessary, these limits every eight years. In conducting such a review,

we will analyze and evaluate the availability of new mercury control technologies installed since the previous review, and to the extent they provide additional cost-effective control, the Agency can move to change the existing NSPS limits. Additionally, the Agency continues to update its understanding of the science associated with mercury emissions, transport, transformation, and deposition, both from ambient data collection and monitoring and through continued enhancements to our analytical tool box. Thus, we feel that OAR and ORD are uniquely positioned to monitor this situation and provide the best possible solution for the protection of public health and the environment.

In closing, we direct the OIG staff to the numerous technical documents supporting the final CAMR, particularly the benefits assessment materials in which we outline in detail the variability associated with methylation and bioaccumulation rates in different water bodies. In these documents, EPA has demonstrated that the conclusions reached in the CAMR are based firmly in sound scientific principles, utilizing the best information available. If your staff have additional questions in researching these documents, our scientists, engineers, and modelers would be happy to assist them.

Sincerely,

William Wehrum
Acting Assistant Administrator
Office of Air and Radiation

George Gray
Assistant Administrator
Office of Research and Development

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United States Environmental Protection Agency
Office of Air Quality Planning and Standards
Research Triangle Park, NC 27711
EPA-454/R-99-005
February 2000
Air

Meteorological Monitoring Guidance for Regulatory Modeling Applications

EPA-454/R-99-005

Meteorological Monitoring Guidance for Regulatory Modeling Applications

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, NC 27711

February 2000

DISCLAIMER

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PREFACE

This document updates the June 1987 EPA document, "On-Site Meteorological Program Guidance for Regulatory Modeling Applications", EPA-450/4-87-013. The most significant change is the replacement of Section 9 with more comprehensive guidance on remote sensing and conventional radiosonde technologies for use in upper-air meteorological monitoring; previously this section provided guidance on the use of sodar technology. The other significant change is the addition to Section 8 (Quality Assurance) of material covering data validation for upper-air meteorological measurements. These changes incorporate guidance developed during the workshop on upper-air meteorological monitoring in July 1998.

Editorial changes include the deletion of the “on-site” qualifier from the title and its selective replacement in the text with “site specific”; this provides consistency with recent changes in Appendix W to 40 CFR Part 51. In addition, Section 6 has been updated to consolidate and provide necessary context for guidance in support of air quality dispersion models which incorporate boundary layer scaling techniques.

The updated document (like the June 1987 document) provides guidance on the collection of meteorological data for use in regulatory modeling applications. It is intended to guide the EPA Regional Offices and States in reviewing proposed meteorological monitoring plans, and as the basis for advice and direction given to applicants by the Regional Offices and States. To facilitate this process, recommendations applicable to regulatory modeling applications are summarized at the end of each section. Alternate approaches, if these recommendations can not be met, should be developed on a case-by-case basis in conjunction with the Regional Office.

ACKNOWLEDGMENTS

The original (June 1987) document was prepared by the On-site Meteorological Data Work Group, formed in December 1985 and chaired by Roger Brode, EPA-OAQPS. Its members and their contributions are as follows: Edward Bennett, NY State DEC, Section 6.6; Roger Brode, EPA-OAQPS, Sections 1.0, 2.0 and 4.0; James Dicke, EPA-OAQPS, Section 5.2; Robert Eskridge, EPA-ASRL, Sections 6.2 and 6.3; Mark Garrison, EPA-Region III, Sections 3.2 and 9.0; John Irwin, EPA-ASRL, Sections 6.1 and 6.4; Michael Koerber, EPA-Region V, Sections 3.1 and 3.3; Thomas Lockhart, Meteorological Standards Institute, Section 8.0; Timothy Method, EPA-Region V, Section 3.4; Stephen Perkins, EPA-Region I, Sections 6.5 and 7.0; and Robert Wilson, EPA-Region 10, Sections 5.1 and 8.6, and parts of Sections 8.1, 8.2, and 8.5. Through their internal reviews and discussions, all of the work group members contributed to shaping the document as a whole. The work group wishes to acknowledge the time and effort of those, both within and outside of EPA, who provided technical review comments on the document. The work group also acknowledges the support and helpful guidance of Joseph A. Tikvart, EPA-OAQPS.

The June 1995 reissue of the document was prepared by Desmond T. Bailey with secretarial assistance from Ms. Brenda Cannady. Technical advice and guidance was provided by John Irwin.

The February 1999 reissue of the document provides updated material for Sections 8 (Quality Assurance) and 9 (Upper-Air Meteorological Monitoring). This material is the product of a workshop conducted at EPA facilities in Research Triangle Park, NC in July 1998. The workshop was conducted for EPA by Sharon Douglas of Systems Applications Inc. and three expert chairpersons: Ken Schere (U.S. EPA); Charles (Lin) Lindsey (Northwest Research Associates, Inc.); and Thomas Lockhart (Meteorological Standards Institute). Participants to the workshop were selected based on their expertise in atmospheric boundary layer measurements and/or the use of such data in modeling. Workshop participants were provided copies of the mock-up for review prior to the workshop, and were tasked to finalize the document during the workshop. The mock-up was prepared by Desmond Bailey (U.S. EPA) based on a draft report prepared under contract to EPA by Sonoma Technology, Inc. (SAI) entitled, "Guidance for Quality Assurance and Management of PAMS Upper-Air Meteorological Data". The latter report was written by Charles Lindsey and Timothy Dye (SAI) and Robert Baxter (Parsons Engineering Science Inc).

The two dozen participants to the workshop represented various interest groups including: remote sensing equipment vendors; local, state, and federal regulatory staff; the NOAA laboratories; university staff; and private consultants. Participants to the workshop were as follows: Desmond T. Bailey (Host), Alex Barnett (AVES), Mike Barth (NOAA Forecast Systems Lab), Bob Baxter (Parsons Engineering Science, Inc.), William B. Bendel (Radian International, LLC), Jerry Crescenti (U.S. Department of Commerce/NOAA), Sharon Douglas (Systems Applications Intl., Inc, Workshop Coordinator), Tim Dye (Sonoma Technology, Inc.), Leo Gendron (ENSR), Gerry Guay (Alaska Dept. of Environmental Conservation), Mark Huncik (CP&L), John Higuchi (SCAQMD), John Irwin (U.S. Environmental Protection Agency. Host),

David Katz (Climatronics), Shawn Kendall (Phelps Dodge Corporation), Don Lehrman (T & B Systems), Charles (Lin) Lindsey (Northwest Research Associates, Inc., Chairperson), Thomas Lockhart (Meteorological Standards Institute, Chairperson), Louis Militana (Roy F. Weston, Inc), Bill B. Murphey (Georgia Dept. of Natural Resources), Kenneth L. Schere (U.S. Environmental Protection Agency ORD, Chairperson), Nelson Seaman (Pennsylvania State University), Dr. Volker Thiermann (SCINTEC Atmospharemesstechnik AG), Stan Vasa (Southern Company Services), John White (North Carolina Division of Air Quality), Dr. J. Allen Zak (NASA Langley Research Center/VIGYAN, Inc.).

Peer review of the an April 1999 draft of this document was provided by Rob Wilson (U.S. EPA, Region 10) and Larry Truppi (U.S. EPA, NERL).

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1. INTRODUCTION

1.1 Background

This document provides guidance for the collection and processing of meteorological data for general use in air quality modeling applications. Such applications include those required in support of air quality regulations as specified in the Guideline on Air Quality Models. Guidance which specifically relates to a regulatory application is so indicated; in addition, recommendations affecting regulatory modeling applications are summarized at the end of individual sections.

Guidance is provided for the in situ monitoring of primary meteorological variables (wind direction, wind speed, temperature, humidity, pressure, and radiation) for remote sensing of winds, temperature, and humidity, and for processing of derived meteorological variables such as stability, mixing height, and turbulence. Most of the guidance is generic in that it supports most categories of air quality models including: steady-state, non-steady-state, Gaussian, and non-Gaussian models. However, material in some sections is probably more useful in support of some types of models than others. For example, the primary focus of the guidance on site selection (Section 3) is the collection of data at single locations for support of steady-state modeling applications. Non-steady-state modeling applications generally require gridded meteorological data using measurements at multiple sites. Support for such applications is provided to the extent that this guidance may be used for selecting sites to monitor the significant meteorological regimes that may need to be represented in these applications. Site selection criteria in these cases must be evaluated in concert with the objectives of the overall network; this falls in the category of network design and is beyond the scope of this document. Similarity, though generically useful, the guidance on upper-air meteorological monitoring (Section 9) is perhaps most useful in support of applications employing gridded meteorological data bases.

One of the most important decisions in preparing for an air quality modeling analysis involves the selection of the meteorological data base; this is the case whether one is selecting a site for monitoring, or selecting an existing data base. These decisions almost always lead to similar questions: “Is the site (are the data) representative?” This question is addressed in Section 3.1.

Minimal guidance is provided on the use of airport data; e.g., for use in filling gaps in site-specific data bases (Section 6.8). For practical purposes, because airport data were readily available, most regulatory modeling was initially performed using these data; however, one should be aware that airport data, in general, do not meet this guidance. The significant deviations to this guidance are discussed in Section 6.7.

The following documents provide necessary background and documentation for this guidance and are incorporated by reference: "Guideline on Air Quality Models" as published in Appendix W to 40 CFR Part 51 **[1]**; "Quality Assurance Handbook for Air Pollution Measurement Systems: Volume IV. Meteorological Measurements" **[2]**; "On-site

Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources" **[3]**, "Standard for Determining Meteorological Information at Nuclear Power Sites" **[4]**.

1.2 Organization of Document

Section 2 provides general information on the instruments used for in-situ measurements of wind speed, wind direction, temperature, temperature difference, humidity, precipitation, pressure, and solar radiation. These variables are considered primary in that they are generally measured directly.

Section 3 provides guidance on siting and exposure of meteorological towers and sensors for the in-situ measurement of the primary meteorological variables. Specific guidance is provided for siting in simple terrain (Section 3.2), complex terrain (Section 3.3), coastal locations (Section 3.4), and urban locations (Section 3.5). The issue of representativeness is addressed in Section 3.1.

Section 4 provides guidance for recording of meteorological data.

Section 5 provides guidance on system performance.

Section 6 provides guidance for processing of meteorological data.

Section 7 provides guidance on data reporting and archiving.

Section 8 provides guidance on the quality assurance and quality control.

Section 9 provides guidance for the most widely used technologies employed for monitoring upper-air meteorological conditions; these include radiosondes and ground-based remote sensing platforms: sodar (Sound Detection and Ranging), radar (Radio Detection and Ranging), and RASS (Radio Acoustic Sounding System).

References are listed in Section 10.

2. PRIMARY METEOROLOGICAL VARIABLES

This section provides general information on the instruments used for in situ measurements of wind speed, wind direction, temperature, temperature difference, humidity, precipitation, pressure, and solar radiation. These variables are considered primary in that they are generally measured directly. Derived variables, such as atmospheric stability, mixing height, and turbulence are discussed in Section 6. Remote sensing platforms for measurements of winds, temperature, and humidity are discussed in Section 9; these variables, when determined using remote sensing, are not measured directly, but are derived from other measurements.

The choice of an instrument for a particular application should be guided by the data quality objectives of the application; as a minimum, these objectives should include the accuracy and resolution of the data needed by the application - recommended data quality objectives for regulatory dispersion modeling applications are provided in Section 5.0. Other considerations which may compete with the data quality objectives include the cost of the instrument, the need for and cost of routine maintenance, and the competing needs of ruggedness and sensitivity. One should also note that the cost of a successful monitoring program does not end with the purchase of the sensors; depending on the instrument, additional costs may be incurred for signal conditioning and recording hardware. There are also the costs involved in siting, installation, and calibration of the equipment, as well as costs associated with the quality assurance and processing of the data.

The focus in the following is on those classes of instruments that are considered best suited for routine in situ monitoring programs, and which generally have had the widest use. Additional information and illustrations for the instruments described in this section may be found in references **[2]**, **[5]**, **[6]**, **[7]**, and **[8]**.

2.1 Wind Speed

Although wind is a vector quantity and may be measured and processed as such, it is common to measure and/or process the scalar components of the wind vector separately; i.e., wind speed (the magnitude of the wind vector) and wind direction (the orientation of the wind vector). Wind speed determines the amount of initial dilution experienced by a plume, and appears in the denominator of the steady-state Gaussian dispersion equation (in the non-steady-state puff model, the wind speed determines the plume/puff transport). In addition, wind speed is used in the calculation of plume rise associated with point source releases, to estimate aerodynamic effects in downwash calculations, and, in conjunction with other variables, in the determination of atmospheric stability (Section 6.4.4). Instruments used for in situ monitoring of wind speed are of two types: those which employ mechanical sensors (e.g., cup and propeller anenometers) and those which employ non-mechanical sensors (hot wire anenometers and sonic anenometers). The non-mechanical sensors are beyond the scope of this guidance and are not addressed in the following; however, this should not preclude their use. When these types of instruments are to be used in support of regulatory actions, prior approval should be obtained

from the reviewing authority as to how the data will be collected, processed, and quality assurred. Guidance on the use of remote sensing platforms for measuring wind speed is provided in Section 9.

2.1.1 Cup Anemometers

The rotating cup anemometer consists of three, four, and sometimes six hemispherical or cone-shaped cups mounted symmetrically about a vertical axis of rotation. The three cup anemometer is recommended; this design has been shown to exert a more uniform torque throughout a revolution. The rate of rotation of the cups is essentially linear over the normal range of measurements, with the linear wind speed being about 2 to 3 times the linear speed of a point on the center of a cup, depending on the dimensions of the cup assembly and the materials from which the sensor is made **[5]**. Sensors with high accuracy at low wind speeds and a low starting threshold should be used (see Section 5). Light weight materials (e.g., molded plastic or polystyrene foam) should be employed to achieve a starting threshold (lowest speed at which a rotating anemometer starts and continues to turn when mounted in its normal position) of $\leq$ 0.5 m/s.

2.1.2 Vane-oriented and Fixed-mount Propeller Anemometers

The vane-oriented propeller anemometer usually consists of a two, three or four-balded propeller which rotates on a horizontal pivoted shaft that is turned into the wind by a vane. Most current versions of this type of anemometer use propellers that are based on a modified helicoid. The dynamic characteristics of the vane should be matched with those of the propeller.

There are several propeller anemometers which employ lightweight molded plastic or polystyrene foam for the propeller blades to achieve threshold speeds of $\leq$ 0.5 m/s. This type of anemometer may be applied to collecting mean wind speeds for input to models to determine dilution estimates and/or transport estimates. Because of their relatively quick response times, some having distance constants of about one meter, these sensors are also suitable for use in determining the standard deviation of the along-wind-speed fluctuations, σ_u. Care should be taken, however, in selecting a sensor that will provide an optimal combination of such characteristics as durability and sensitivity for the particular application.

The variation of output speed with the approach angle of the wind follows nearly a cosine response for some helicoid propeller anemometers. This relationship permits the use of two orthogonal fixed-mount propellers to determine the vector components of the horizontal wind. A third propeller with a fixed mount rotating about a vertical axis may be used to determine the vertical component of the wind, and also the standard deviation of the vertical wind, σ_w. It should be noted that deviation of the response from a true cosine for large approach angles (e.g., 80-90°) may lead to underestimations of the vertical wind component without special calibration of the output signal. Users of vertical propeller anemometers should consult with the manufacturer on proper handling of the data.

2.1.3 Wind Speed Transducers

There are several mechanisms that can be used to convert the rate of the cup or propeller rotations to an electrical signal suitable for recording and/or processing. The four most commonly used types of transducers are the DC generator, the AC generator, the electrical-contact, and the interrupted light beam. Many DC and AC generator types of transducers in common use have limitations in terms of achieving low thresholds and quick response times. Some DC generator transducers are limited because the combined effect of brush and bearing friction give a threshold speed above 0.5 m/s (above 1.0 mph). However, some anemometers employ miniaturized DC generators which allow thresholds below 0.5 m/s to be achieved. The AC generator transducers eliminate the brush friction, but care must be exercised in the design of the signal conditioning circuitry to avoid spurious oscillations in the output signal that may be produced at low wind speeds. Electrical-contact transducers are used to measure the "run-of-the-wind"; i.e., the amount of air (measured as a distance) passing a fixed point in a given time interval; wind speed is calculated by dividing run-of-the-wind measurements by the time interval. The interrupted light beam (light chopping) transducer is frequently used in air quality applications because of the lower threshold that can be achieved by the reduction in friction. This type of transducer uses either a slotted shaft or a slotted disk, a photo emitter and a photo detector. The cup or propeller assembly rotates the slotted shaft or disk, creating a pulse each time the light passes through a slot and falls on the photo detector. The frequency output from this type of transducer is handled in the same way as the output from an AC generator. Increasing the number of slots to about 100, thereby increasing the pulse rate, eliminates signal conditioning problems which may arise with lower frequencies. The frequency output from an AC generator or a light chopping transducer may be transmitted through a signal conditioner and converted to an analog signal for various recording devices, such as a continuous strip chart or a multi point recorder, or through an analog-to-digital (A/D) converter to a microprocessor type of digital recorder. Several modern data loggers can accept the frequency type signal directly, eliminating the need for additional signal conditioning. The recording and processing of the data are covered in more detail in Sections 4.0 and 6.0, respectively.

2.2 Wind Direction

Wind direction is generally defined as the orientation of the wind vector in the horizontal. Wind direction for meteorological purposes is defined as the direction <u>from</u> which the wind is blowing, and is measured in degrees clockwise from true north. Wind direction determines the transport direction of a plume or puff in air quality modeling applications. The standard deviation of the wind direction, σ_A, or the standard deviation of the elevation angle, σ_E, may also be used, in conjunction with wind speed, to derive the atmospheric stability category (Section 6.4). Wind direction may be measured directly using a wind vane (Section 2.2.1) or may be derived from measurements of wind speed components (Section 2.2.2).

2.2.1 Wind Vanes

The conventional wind vane consists of a tail section attached to one end of a horizontal shaft which, in turn, is mounted on a vertical axis; the tail and shaft rotate in a horizonal plane. The wind vane measures the azimuth angle of the wind. Wind vanes and tail fins should be constructed from light weight materials. The starting threshold (lowest speed at which a vane will turn to within 5° of the true wind direction from an initial displacement of 10°) should be $\leq$ 0.5 ms^{-1}. Overshoot must be $\leq$ 25% and the damping ratio should lie between 0.4 and 0.7.

Bi-directional vanes (bivanes) measure both the azimuth and elevation angles of the wind vector. The bivane generally consists of either an annular fin or two flat fins perpendicular to each other, counterbalanced and mounted on a gimbal so that the unit can rotate freely both horizontally and vertically. Bivanes require greater care and are not generally suited for routine monitoring. Data from bivanes, consequently, should only be used on a case by case basis with the approval of the reviewing authority.

2.2.2 U-V and UVW Systems

Another method of obtaining the horizontal and/or vertical wind direction is through the use of orthogonal fixed-mount propeller anemometers, the U-V or UVW systems. The horizontal and, in the case of UVW systems, the vertical, wind direction can be determined computationally from the orthogonal wind speed components. The computational methods are based on the fact that the variation of output speed with the approach angle of the wind follows nearly a cosine response for some helicoid propeller anemometers.

2.2.3 Wind Direction Transducers

Many kinds of simple commutator type transducers utilize brush contacts to divide the wind direction into eight or 16 compass point sectors. However, these transducers do not provide adequate resolution to characterize transport for most air quality modeling applications.

A fairly common transducer for air quality modeling applications is a 360° potentiometer. The voltage across the potentiometer varies directly with the wind direction. A commonly used solution to the discontinuity that occurs across the small gap in a single potentiometer is to place a second potentiometer 180° out of phase with the first one **[5]**. In this case the voltage output corresponds to a 0° to 540° scale. This transducer utilizes a voltage discriminator to switch between the "upper" and "lower" potentiometers at appropriate places on the scale. This technique eliminates chart "painting" which occurs on strip chart recorders when the wind oscillates across north (i.e., between 0 and full scale). A disadvantage is that chart resolution is reduced by one third.

Another type of transducer being used is a wind direction resolver, which is a variable phase transformer where the phase change is a function of the shaft rotation angle. This system alleviates the maintenance problems associated with the friction caused by the wiper in a

potentiometer; however, this type of transducer is more expensive and requires more complex signal conditioning circuity.

2.2.4 Standard Deviation and Turbulence Data

The standard deviation of the azimuth and elevation angles of the wind vector, σ_A and σ_E, respectively can be related to the dispersive capabilities of the atmosphere, in particular, to the dispersion coefficients σ_y and σ_z which characterize plume concentration distributions in commonly-used Gaussian models. These quantities can be used as inputs to algorithms to determine Pasquill stability categories (see Section 6.4.4), or may also be treated as turbulence data for direct input to certain Gaussian models. The σ values should be computed directly from high-speed analog or digital data records (Section 6.1). If a sigma meter or sigma computer is used, care should be taken that the results are not biased by smoothing of the data, and to ensure that the methods employed accurately treat the 0-360° crossover and use an adequate number of samples (at least 360 per averaging period, see Section 6.1.4). The comparability of results from the sigma computer to the direct statistical approach should be demonstrated. To accurately determine σ_A and σ_E, the wind direction sensors must possess certain minimum response characteristics. The most important in this regard is the damping ratio, which should be between 0.4 to 0.7 (see Section 5.2). The wind direction should also be recorded to a resolution of 1 degree in order to calculate the standard deviation.

2.3 Temperature and Temperature Difference

This section addresses both the measurement of ambient air temperature at a single level and the measurement of the temperature difference between two levels. The ambient temperature is used in determining the amount of rise experienced by a buoyant plume. The vertical temperature difference is used in calculating plume rise under stable atmospheric conditions, and is also used in determining Monin-Obukhov length, a stability parameter (Section 6.4.5).

2.3.1 Classes of Temperature Sensors

Sensors used for monitoring ambient temperature include: wire bobbins, thermocouples, and thermistors. Platinum resistance temperature detectors (RTD) are among the more popular sensors used in ambient monitoring; these sensors provide accurate measurements and maintain a stable calibration over a wide temperature range. The RTD operates on the basis of the resistance changes of certain metals, usually platinum or copper, as a function of temperature. These two metals are the most commonly used because they show a fairly linear increase of resistance with rising temperature **[5]**. "Three wire" and "four wire" RTDs are commonly used to compensate for lead resistance errors. A second type of resistance change thermometer is the thermistor, which is made from a mixture of metallic oxides fused together. The thermistor generally gives a larger resistance change with temperature than the RTD. Because the relation between resistance and temperature for a thermistor is non-linear, systems generally are designed

to use a combination of two or more thermistors and fixed resistors to produce a nearly linear response over a specific temperature range **[5, 8]**.

Thermoelectric sensors work on the principle of a temperature dependent electrical current flow between two dissimilar metals. Such sensors, called thermocouples, have some special handling requirements for installation in order to avoid induction currents from nearby AC sources, which can cause errors in measurement **[5]**. Thermocouples are also susceptible to spurious voltages caused by moisture. For these reasons, their usefulness for routine field measurements is limited.

2.3.2 Response Characteristics

The response of temperature sensors can be characterized by a first order linear differential equation. The time constant for temperature sensors, i.e. the time taken to respond to 63% of a step change in the temperature, is a function of the air density and wind speed or ventilation rate. The time constant for a mercury-in-glass thermometer is about l minute for a ventilation rate of 5 m/s **[5, 6]**. Time constants for platinum resistance temperature detectors (RTDs) and for thermistors mounted in a typical probe are about 45 seconds. These are adequate response times for monitoring programs (see Section 5.2).

2.3.3 Temperature Difference

The basic sensor requirements for measuring vertical temperature difference are essentially the same as for a simple ambient temperature measurement. However, matched sensors and careful calibration are required to achieve the desired accuracy of measurement. The ambient temperature measurement is often taken from one of the sensors used to measure the differential temperature. A number of systems are commercially available that utilize a special translator module to process the signal difference between the two component sensors. Through signal processing, the accuracy of the differential temperature can be calibrated to the level of resolution of the component systems.

2.3.4 Sources of Error

One of the largest sources of error in any temperature system is due to solar radiation. Temperature sensors must be adequately shielded from the influences of direct or reflected solar radiation in order to provide representative measurements. A well ventilated shelter may be adequate for surface temperature measurements but would be impractical for levels higher than a few meters above ground. Tower-mounted sensors are generally housed in aspirated radiation shields. It is advisable to utilize motor driven aspirators to ensure adequate ventilation. Care should also be taken that moisture not be allowed to come in contact with the sensor or the inside surfaces of the radiation shield. In some sensors moisture will change the electrical properties of the sensor, causing error. In others, the evaporative cooling will cause the temperature reading to

be too low. For temperature difference measurements, sensors should be housed in identical aspirated radiation shields with equal exposures.

2.4 Humidity

2.4.1 Humidity Variables

Humidity is a general term related to the amount of moisture in the air; humidity variables include vapor pressure, dew point temperature, specific humidity, absolute humidity, and relative humidity. With the exception of relative humidity, all of the above variables provide a complete specification of the amount of water vapor in the air; in the case of relative humidity, measurements of temperature and pressure are also required. Humidity is an important variable in determining impacts from moist sources, such as cooling towers; it is also used in modeling ozone chemistry.

2.4.2 Types of Instrumentation

There are basically two types of sensors for measuring humidity, psychrometers and hygrometers. The psychrometer, consists of two thermometers, one of which is covered with a wet wick (the wet bulb) and a mechanism for ventilating the pair. Evaporation lowers the temperature of the wet bulb; the difference in temperature from the dry bulb (the wet bulb depression) is a measure of the amount of moisture in the air. While still in use at many observing stations, psychrometers are generally not suitable for routine monitoring programs. However, they can be used as secondary standards in audit procedures.

Hygrometers are a class of instruments that measure the physical effect that moisture has on a substances, such as hair. For example, the lithium chloride hygrometer uses a probe impregnated with lithium chloride solution. Voltage is supplied to the electrodes in the probe until an equilibrium temperature is reached based on the conductivity of the lithium chloride. The dew point hygrometer, uses a cooled mirror as a sensor; in this case, the temperature of the mirror is monitored to determine the temperature at which dew (or frost) first appears. Such condensation typically disrupts the path of a light beam reflecting off of the cooled surface, causing it to be heated until the condensation disappears. Once the condensation is gone, the surface is cooled again until condensation forms. These oscillating heating and cooling cycles define an average dew point temperature. The temperature of the surface is typically measured by a linear thermistor or a platinum RTD. The thin film capacitor hygrometer measures humidity by detecting the change in capacitance of a thin polymer film; this sensor has a relatively fast response compared to other types of hygrometers.

If possible, humidity sensors should be housed in the same aspirated radiation shield as the temperature sensor. The humidity sensor should be protected from contaminants such as salt, hydrocarbons, and other particulates. The best protection is the use of a porous membrane filter which allows the passage of ambient air and water vapor while keeping out particulate matter.

2.5 Precipitation

Precipitation data, although primarily used in wet deposition modeling, are also used for consistency checks in data review and validation. The two main classes of precipitation measuring devices suitable for meteorological programs are the tipping bucket rain gauge and the weighing rain gauge. Both types of gauge measure total liquid precipitation. Both types of gauge may also be used to measure the precipitation rate, but the tipping bucket is preferable for that application. A third type, the optical rain gauge, has not yet been adequately developed for widespread use.

The tipping bucket rain gauge is probably the most common type of instrument in use for meteorological programs. The rainfall is collected by a cylinder, usually about 8 to 12 inches in diameter, and funneled to one of two small "buckets" on a fulcrum. Each bucket is designed to collect the equivalent of 0.01 inches (0.3 mm) of precipitation, then tip to empty its contents and bring the other bucket into position under the funnel. Each tip of the bucket closes an electrical contact which sends a signal to a signal conditioner for analog and/or digital recording. These are fairly reliable and accurate instruments. Measurement errors may occur if the funnel is too close to the top of the cylinder, resulting in an underestimate of precipitation due to water splashing out of the cylinder, especially during heavy rainfall. Underestimates may also occur during heavy rainfall because precipitation is lost during the tipping action. Inaccuracies may also result if the tipping bucket assembly or the entire gauge is not leveled properly when installed. Tipping buckets are generally equipped with heaters to melt the snow in cold climates, however, the total precipitation may be underestimated due to evaporation of the frozen precipitation caused by the heating element. It would be preferable for the heater to be thermostatically controlled, rather than operate continuously, to avoid underestimation due to evaporation that may also occur during periods of light rain or drizzle. Underestimation of precipitation, especially snowfall, may also result from cases where the gauge is not adequately sheltered from the influence of the wind. A wind shield should therefore be used in climates that experience snowfall. Strong winds can also cause the buckets to tip, resulting in spurious readings.

The weighing rain gauge has the advantage that all forms of precipitation are weighed and recorded as soon as they fall into the gauge. No heater is needed to melt the snow, except to prevent snow and ice buildup on the rim of the gauge, alleviating the problem of evaporation of snow found with the heated tipping bucket gauge. Antifreeze is often used to melt the snow in the bucket. However, the weighing gauge requires more frequent tending than the tipping bucket gauge, and is more sensitive to strong winds causing spurious readings. The weight of precipitation is recorded on a chart mounted on a clock-driven drum for later data reduction. Weighing systems are also available which provide an electrical signal for digital processing.

2.6 Pressure

Atmospheric or barometric pressure can provide information to the meteorologist responsible for reviewing data that may be useful in evaluating data trends, and is also used in

conjunction with air quality measurements. There are two basic types of instruments available for measuring atmospheric pressure, the mercury barometer and the aneroid barometer.

The mercury barometer measures the height of a column of mercury that is supported by the atmospheric pressure. It is a standard instrument for many climatological observation stations, but it does not afford automated data recording.

Another common type of pressure instrument is the aneroid barometer which consists of two circular disks bounding an evacuated volume. As the pressure changes, the disks flex, changing their relative spacing which is sensed by a mechanical or electrical element and transmitted to a transducer. A barograph is usually an aneroid barometer whose transducer is a mechanical linkage between the bellows assembly and an ink pen providing a trace on a rotating drum. A more sophisticated aneroid barometer providing a digital output has been developed consisting of a ceramic plate substrate sealed between two diaphragms. Metallic areas on the ceramic substrate form one plate of a capacitor, with the other plate formed by the two diaphragms. The capacitance between the internal electrode and the diaphragms increases linearly with applied pressure. The output from this barometer is an electronic signal that can be processed and stored digitally **[5]**.

2.7 Radiation

Solar and/or net radiation data are used to determine atmospheric stability (Section 6.4.2), for calculating various surface-layer parameters used in dispersion modeling (Section 6.6), for estimating convective (daytime) mixing heights, and for modeling photochemical reactions.

Solar radiation refers to the electromagnetic energy in the solar spectrum (0.10 to 4.0 µm wavelength); the latter is commonly classified as ultraviolet (0.10 to 0.40 µm), visible light (0.40 to 0.73 µm), and near-infrared (0.73 to 4.0 µm) radiation. Net radiation includes both solar radiation (also referred to as short-wave radiation) and terrestrial or long-wave radiation; the sign of the net radiation indicates the direction of the flux (a negative value indicates a net upward flux of energy).

Pyranometers are a class of instruments used for measuring energy fluxes in the solar spectrum. These instruments are configured to measure what is referred to as global solar radiation; i.e., direct plus diffuse (scattered) solar radiation incidence on a horizontal surface. The sensing element of the typical pyranometer is protected by a clear glass dome which both protects the sensing element, and functions as a filter preventing entry of energy outside the solar spectrum (i.e., long-wave radiation). The glass domes used on typical pyranometers are transparent to wavelengths in the range of 0.28 to 2.8 µm. Filters can be used instead of the clear glass dome to measure radiation in different spectral intervals; e.g., ultraviolet radiation.

WMO specifications for several classes of pyranometers are given in Table 2-1 **[9]**. First class and secondary standard pyranometers typically employ a thermopile for the sensing element. The thermopile consists of a series of thermojunction pairs, an optically black primary junction, and an optically white reference junction (in some pyranometers, the reference

thermojunction is embedded in the body of the instrument). The temperature difference between the primary and reference junctions which results when the pyranometer is operating generates an electrical potential proportional to the solar radiation. Second class pyranometers typically employ photo-cells for the sensing element. Though less costly than other types of pyranometers, the spectral response of the photovoltaic pyranometer is limited to the visible spectrum.

First class or second class pyranometers should normally be used for measuring global solar radiation, depending on the application. If the solar radiation data are to be used in procedures for estimating stability (Section 6.4) then second class (photovoltaic) pyranometers are acceptable. For most other applications, first class or secondary standard pyranometers should be used. Applications requiring ultraviolet (UV) radiation data should not employ photovoltaic measurements as these instruments are not sensitive to UV radiation.

Table 2-1

Classification of Pyranometers [9]

Characteristic	Units	Secondary Standard	First Class	Second Class
Resolution	$W\ m^{-2}$	±1	±5	±10
Stability	%FS*	±1	±2	±5
Cosine Response	%	< ±3	< ±7	< ±15
Azimuth Response	%	< ±3	< ±5	< ±10
Temperature Response	%	±1	±2	±5
Nonlinearity	%FS*	±0.5	±2	±5
Spectral Sensitivity	%	±2	±5	±10
Response Time (99%)	seconds	< 25	< 60	< 240

* Percent of full scale

2.8 Recommendations

Light weight three cup anemometers (Section 2.1.1) or propeller anemometers (Section 2.1.2) should be used for measuring wind speed. Sensors with high accuracy at low wind speeds and a low starting threshold should be used (see Section 5). Light weight, low friction systems which meet the performance specifications given in Section 5.0 should be used. Heaters should be employed to protect against icing in cold climates. Sonic anenometers and hot wire

anenometers may be used with the approval of the reviewing authority. These instruments are especially suited for use in direct measurements of turbulence.

Wind direction should be measured directly using a wind vane (Section 2.2.1) or may be derived from measurements of wind speed components (Section 2.2.2). Light weight, low friction systems which meet the performance specifications given in Section 5.0 should be used. Heaters should be employed to protect against icing in cold climates. Bivanes are regarded as research grade instruments and are not generally suited for routine monitoring. Data from bivanes may be used on a case by case basis with the approval of the reviewing authority.

Temperature and temperature difference should be measured using resistance temperature devices which meet the performance specifications of Section 5.0. Thermoelectric sensors (thermocouples) are not recommended because of their limited accuracy and complex circuitry.

Humidity should be measured using a dew point, lithium chloride, or thin-film capacitor hygrometer. The hygrometer should meets the performance specifications in Section 5.0.

Precipitation should be measured with a weighing or tipping bucket rain gauge. In cold climates, the gauge should be equipped with a heater and a wind shield.

Atmospheric pressure should be measured with an aneroid barometer which meets the performance specifications given in Section 5.0

First class or second class pyranometers should normally be used for measuring global solar radiation, depending on the application. If the solar radiation data are to be used in procedures for estimating stability (Section 6.4) then second class (photovoltaic) pyranometers are acceptable. For most other applications, first class or secondary standard pyranometers should be used. Applications requiring ultraviolet (UV) radiation data should not employ photovoltaic measurements as these instruments are not sensitive to UV radiation.

Recommended performance specifications for the primary meteorological variables are provided in Table 5-1.

3. SITING AND EXPOSURE

This section provides guidance on siting and exposure of meteorological towers and sensors for the in situ measurement of the primary meteorological variables. Specific guidance is provided for siting in simple terrain (Section 3.2), in complex terrain (Section 3.3), in coastal locations (Section 3.4), and in urban locations (Section 3.5). The issue of representativness is addressed in Section 3.1.

As a general rule, meteorological sensors should be sited at a distance which is beyond the influence of obstructions such as buildings and trees; this distance depends upon the variable being measured as well as the type of obstruction. The other general rule is that the measurements should be representative of meteorological conditions in the area of interest; the latter depends on the application. Secondary considerations such as accessibility and security must be taken into account, but should not be allowed to compromise the quality of the data. In addition to routine quality assurance activities (see Section 8), annual site inspections should be made to verify the siting and exposure of the sensors. Approval for a particular site selection should be obtained from the permit granting agency prior to any site preparation activities or installation of any equipment.

3.1 Representativeness

One of the most important decisions in preparing for an air quality modeling analysis involves the selection of the meteorological data base; this is the case whether one is selecting a site for monitoring, or selecting an existing data base. These decisions almost always lead to similar questions: “Is the site (are the data) representative?” Examples eliciting a negative response abound; e.g., meteorological data collected at a coastal location affected by a land/sea breeze circulation would generally not be appropriate for modeling air quality at an inland site located beyond the penetration of the sea breeze. One would hope that such examples could be used in formulating objective criteria for use in evaluating representativeness in general. Though this remains a possibility, it is not a straight forward task - this is due in part to the fact that representativeness is an exact condition; a meteorological observation, data base, or monitoring site, either is, or is not representative within the context of whatever criteria are prescribed. It follows that, a quantitative method does not exist for determining representativeness absolutely. Given the above, it should not be surprising that there are no generally accepted analytical or statistical techniques to determine representativeness of meteorological data or monitoring sites.

3.1.1 Objectives for Siting

Representativeness has been defined as "the extent to which a set of measurements taken in a space-time domain reflects the actual conditions in the same or different space-time domain taken on a scale appropriate for a specific application" **[10]**. The space-time and application aspects of the definition as relates to site selection are discussed in the following.

In general, for use in air quality modeling applications, meteorological data should be representative of conditions affecting the transport and dispersion of pollutants in the "area of interest" as determined by the locations of the sources and receptors being modeled. In many instances, e.g. in complex terrain, multiple monitoring sites may be required to adequately represent spatial variations in meteorological conditions affecting transport and/or dispersion.

In steady-state modeling applications, one typically focuses on the meteorological conditions at the release height of the source or sources, or the plume height in the case of buoyant sources. Representativeness for steady-state modeling applications must necessarily be assessed in concert with the steady-state assumption that meteorological conditions are constant within the space-time domain of the application; as typically applied, measurements for a single location, somewhere near the source, are assumed to apply, without change, at all points in the modeling domain. Consistency would call for site selection criteria consistent with the steady-state assumption; i.e., to the extent possible, sites should perhaps be selected such that factors which cause spatial variations in meteorological conditions, are invariant over the spatial domain of the application, whatever that might be. Such factors would include surface characteristics such as ground cover, surface roughness, the presence or absence of water bodies, etc. Similarly, the representativeness of existing third-party data bases should be judged, in part, by comparing the surface characteristics in the vicinity of the meteorological monitoring site with the surface characteristics that generally describe the analysis domain.

Representativeness has an entirely different interpretation for non-steady-state modeling applications which commonly employ three dimensional gridded meteorological fields based on measurements at multiple sites. The meteorological processors which support these applications are designed to appropriately blend available NWS data, local site-specific data, and prognostic mesoscale data; empirical relationships are then used to diagnostically adjust the wind fields for mesoscale and local-scale effects **[11]**, **[12]** . These diagnostic adjustments can be improved through the use of strategically placed site-specific meteorological observations. Support for such applications is provided to the extent that this guidance can be used for selecting sites to monitor the significant meteorological regimes that may need to be represented in these applications. Site selection for such applications (often more than one location is needed) falls in the category of network design and is beyond the scope of this document. Model user's guides should be consulted for meteorological data requirements and guidance on network design for these applications.

3.1.2 Factors to Consider

Issues of representativeness will always involve case-by-case subjective judgements; consequently, experts knowledgeable in meteorological monitoring and air quality modeling should be included in the site selection process. The following information is provided for consideration in such decisions. Readers are referred to a 1982 workshop report **[10]** on representativeness for further information on this topic.

- It is important to recognize that, although certain meteorological variables may be considered unrepresentative of another site (for instance, wind direction or wind speed), other variables may be representative (such as temperature, dew point, cloud cover). Exclusion of one variable does not necessarily exclude all. For instance, one can argue that weather observations made at different locations are likely to be similar if the observers at each location are within sight of one another - a stronger argument can be made for some types of observations (e.g., cloud cover) than others. Although, by no means a sufficient condition, the fact that two observers can "see" one another supports a conclusion that they would observe similar weather conditions.
- In general, the representativeness of the meteorological data used in an air quality modeling analysis is dependent on the proximity of the meteorological monitoring site to the “area-of-interest”.
- Spatial representativeness of the data will almost always be adversely affected (degraded) by increasing the distance between the sources and receptors (increasing the size of the area-of-interest).
- Although proximity of the meteorological monitoring site is an important factor, representativeness is not simply a function of distance. In some instances, even though meteorological data are acquired at the location of the pollutant source, they may not correctly characterize the important atmospheric dispersion conditions; e.g., dispersion conditions affecting sources located on the coast are strongly affected by off-shore air/sea boundary conditions - data collected at the source would not always reflect these conditions.
- Representativeness is a function of the height of the measurement. For example, one can expect more site-to-site variability in measurements taken close to the surface compared to measurements taken aloft. As a consequence, upper-air measurements are generally representative of much larger spatial domains then are surface measurements.
- Where appropriate, data representativeness should be viewed in terms of the appropriateness of the data for constructing realistic boundary layer profiles and three dimensional meteorological fields.
- Factors that should be considered in selecting a monitoring site in complex terrain include: the aspect ratio and slope of the terrain, the ratios of terrain height to stack height and plume height, the distance of the source from the terrain feature, and the effects of terrain features on meteorological conditions, especially wind speed and wind direction.

3.2 Simple Terrain Locations

For the purposes of this guidance, the term “simple terrain” is intended to mean any site where terrain effects on meteorological measurements are non-significant. The definition of significance depends on the application; for regulatory dispersion modeling applications,

significance is determined by comparing stack-top height to terrain height - terrain which is below stack-top is classified as simple terrain **[1]**

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3.2.1 Wind Speed and Wind Direction

3.2.1.1 Probe placement

The standard exposure height of wind instruments over level, open terrain is 10 m above the ground **[9]**. Open terrain is defined as an area where the distance between the instrument and any obstruction is at least ten times the height of that obstruction **[2, 4, 9]**. The slope of the terrain in the vicinity of the site should be taken into account when determining the relative height of the obstruction **[2]**. An obstruction may be man-made (such as a building or stack) or natural (such as a hill or a tree). The sensor height, its height above obstructions, and the height/character of nearby obstructions should be documented. Where such an exposure cannot be obtained, the anemometer should be installed at such a height that it is reasonably unaffected by local obstructions and represents the approximate wind values that would occur at 10 m in the absence of the obstructions. This height, which depends on the extent, height, and distance of obstructions and on site availability, should be determined on a case-by-case basis. Additional guidance on the evaluation of vertical profiles (Section 6.1.3) and surface roughness (Section 6.4.2) may be helpful in determining the appropriate height.

If the source emission point is substantially above 10 m, then additional wind measurements should be made at stack top or 100 m, whichever is lower **[1]**. In cases with stack heights of 200 m or above, the appropriate measurement height should be determined by the Regional Office on a case-by-case basis. Because maximum practical tower heights are on the order of 100 m, wind data at heights greater than 100 m will most likely be determined by some other means. Elevated wind measurements can be obtained via remote sensing (see Section 9.0). Indirect values can be estimated by using a logarithmic wind-speed profile relationship. For this purpose, instruments should be located at multiple heights (at least three) so that site-specific wind profiles can be developed.

3.2.1.2 Obstructions

Buildings. Aerodynamic effects due to buildings and other major structures, such as cooling towers, should be avoided to the extent possible in the siting of wind sensors; such effects are significant, not only in the vicinity of the structures themselves, but at considerable distances downwind. Procedures for assessing aerodynamic effects have been developed from observing such effects in wind tunnels **[13]**, **[14]**. Wind sensors should only be located on building rooftops as a last resort; in such cases, the sensors should be located at a sufficient height above the rooftop to avoid the aerodynamic wake. This height can be determined from on-site measurements (e.g., smoke releases) or wind tunnel studies. As a rule of thumb, the total depth of the building wake is estimated to be approximately 2.5 times the height of the building **[1]**.

Trees. In addition to the general rules concerning obstructions noted above, additional considerations may be important for vegetative features (e.g., growth rates). Seasonal effects should also be considered for sites near deciduous trees. For dense, continuous forests where an open exposure cannot be obtained, measurements should be taken at 10m above the height of the general vegetative canopy.

Towers. Sensors mounted on towers are frequently used to collect wind speed measurements at more than one height. To avoid the influence of the structure itself, closed towers, stacks, cooling towers, and similar solid structures should not be used to support wind instruments. Open-lattice towers are preferred. Towers should be located at or close to plant elevation in an open area representative of the area of interest.

Wind instruments should be mounted on booms at a distance of at least twice the diameter/diagonal of the tower (from the nearest point on the tower) into the prevailing wind direction or wind direction of interest **[2]**. Where the wind distribution is strongly bimodal from opposite directions, such as in the case of up-valley and down-valley flows, then the booms should be at right angles to the predominant wind directions. The booms must be strong enough so that they will not sway or vibrate sufficiently to influence standard deviation values in strong winds. Folding or collapsible towers are not recommended since they may not provide sufficient support to prevent such vibrations, and also may not be rigid enough to ensure proper instrument orientation. The wind sensors should be located at heights of minimum tower density (i.e., minimum number of diagonal cross-members) and above/below horizontal cross-members **[2]**. Since practical considerations may limit the maximum boom length, wind sensors on large towers (e.g., TV towers and fire look-out towers) may only provide accurate measurements over a certain arc. In such cases, two systems on opposite sides of the tower may be needed to provide accurate measurements over the entire 360°. If such a dual system is used, the method of switching from one system to the other should be carefully specified. A wind instrument mounted on top of a tower should be mounted at least one tower diameter/diagonal above the top of the tower structure.

Surface roughness. The surface roughness over a given area reflects man-made and natural obstructions, and general surface features. These roughness elements effect the horizontal and vertical wind patterns. Differences in the surface roughness over the area of interest can create differences in the wind pattern that may necessitate additional measurement sites. A method of estimating surface roughness length, z_o, is presented in Section 6.4.2. If an area has a surface roughness length greater than 0.5 m, then there may be a need for special siting considerations (see discussion in Sections 3.3 and 3.5).

3.2.1.3 Siting considerations

A single well-located measurement site can be used to provide representative wind measurements for non-coastal, flat terrain, rural situations. Wind instruments should be placed taking into account the purpose of the measurements. The instruments should be located over level, open terrain at a height of 10 m above the ground, and at a distance of at least ten times the

height of any nearby obstruction. For elevated releases, additional measurements should be made at stack top or 100 m, whichever is lower **[1]**. In cases with stack heights of 200 m or above, the appropriate measurement height should be determined by the Regional Office on a case-by-case basis.

3.2.2 Temperature, Temperature Difference, and Humidity

The siting and exposure criteria for temperature, temperature difference and humidity are similar. Consequently, these variables are discussed as a group in the following; exceptions are noted as necessary.

3.2.2.1 Probe placement

Ambient temperature and humidity should be measured at 2 m, consistent with the World Meteorological Organization (WMO) standards for ambient measurements **[9]**. Probe placement for temperature difference measurements depend on the application.. For use in estimating surface layer scaling parameters (Section 6.6.4), the temperature difference should be measured between $20z_0$ and $100z_0$; the same recommendation applies to temperature difference measurements for use in estimating the P-G stability category using the solar radiation delta-T method (Section 6.4.4.2). For use in estimating stable plume rise, temperature difference measurements should be made across the plume rise layer, a minimum separation of 50 m is recommended. For sites that experience large amounts of snow, adjustments to the temperature measurement height may be necessary, however, the ambient temperature measurement should not extend above 10 m. For analysis of cooling tower impacts, measurements of temperature and humidity should also be obtained at source height and within the range of final plume height. The measurement of temperature difference for analysis of critical dividing streamline height, H_{crit}, a parameter used in complex terrain modeling, is discussed in Section 3.3.3.

Temperature and humidity sensors should be located over an open, level area at least 9 m in diameter. The surface should be covered by short grass, or, where grass does not grow, the natural earth surface **[2, 9]**. Instruments should be protected from thermal radiation (from the earth, sun, sky, and any surrounding objects) and adequately ventilated using aspirated shields. Forced aspiration velocity should exceed 3 m/s, except for lithium chloride dew cells which operate best in still air **[2]**. If louvered shelters are used instead for protection (at ground level only), then they should be oriented with the door facing north (in the Northern Hemisphere). Temperature and humidity data obtained from naturally-ventilated shelters will be subject to large errors when wind speeds are light (less than about 3 m/s).

Temperature and humidity sensors on towers should be mounted on booms at a distance of about one diameter/diagonal of the tower (from the nearest point on the tower) **[2]**. In this case, downward facing aspiration shields are necessary.

3.2.2.2 Obstructions

Temperature and humidity sensors should be located at a distance of at least four times the height of any nearby obstruction and at least 30 m from large paved areas **[2]**, **[15]**. Other situations to avoid include: large industrial heat sources, rooftops, steep slopes, sheltered hollows, high vegetation, shaded areas, swamps, areas where frequent snow drifts occur, low places that hold standing water after rains, and the vicinity of air exhausts (e.g., from a tunnel or subway) **[2, 9]**.

3.2.2.3 Siting considerations

In siting temperature sensors, care must be taken to preserve the characteristics of the local environment, especially the surface. Protection from thermal radiation (with aspirated radiation shields) and significant heat sources and sinks is critical. Siting recommendations are similar for humidity measurements, which may be used for modeling input in situations involving moist releases, such as cooling towers. For temperature difference measurements, sensors should be housed in identical aspirated radiation shields with equal exposure.

3.2.3 Precipitation

3.2.3.1 Probe placement

A rain gauge should be sited on level ground so the mouth is horizontal and open to the sky **[2]**. The underlying surface should be covered with short grass or gravel. The height of the opening should be as low as possible (minimum: 30 cm), but should be high enough to avoid splashing in from the ground.

Rain gauges mounted on towers should be located above the average level of snow accumulation **[15]**. In addition, collectors should be heated if necessary to properly measure frozen precipitation **[4]**.

3.2.3.2 Obstructions

Nearby obstructions can create adverse effects on precipitation measurements (e.g., funneling, reflection, and turbulence) which should be avoided. On the other hand, precipitation measurements may be highly sensitive to wind speed, especially where snowfall contributes a significant fraction of the total annual precipitation. Thus, some sheltering is desirable. The need to balance these two opposite effects requires some subjective judgment.

The best exposure may be found in orchards, openings in a grove of trees, bushes, or shrubbery, or where fences or other objects act together to serve as an effective wind-break. As a general rule, in sheltered areas where the height of the objects and their distance to the instrument is uniform, their height (above the instrument) should not exceed twice the distance (from the instrument) **[15]**. In open areas, the distance to obstructions should be at least two, and

preferably four, times the height of the obstruction. It is also desirable in open areas which experience significant snowfall to use wind shields such as those used by the National Weather Service **[2, 9, 15]**.

3.2.3.3 Siting considerations

In view of the sensitivity to wind speed, every effort should be made to minimize the wind speed at the mouth opening of a precipitation gauge. This can be done by using wind shields. Where snow is not expected to occur in significant amounts or with significant frequency, use of wind shields is less important. However, the catch of either frozen or liquid precipitation is influenced by turbulent flow at the collector, and this can be minimized by the use of a wind shield.

3.2.4 Pressure

Although atmospheric pressure may be used in some modeling applications, it is not a required input variable for steady-state modeling applications. Moreover, the standard atmospheric pressure for the station elevation may often be sufficient for those applications which require station pressure; the model user's guide should be checked for specific model requirements.

3.2.5 Radiation

3.2.5.1 Probe placement

Pyranometers used for measuring incoming (solar) radiation should be located with an unrestricted view of the sky in all directions during all seasons, with the lowest solar elevation angle possible. Sensor height is not critical for pyranometers. A tall platform or rooftop is a desirable location **[2]**. Net radiometers should be mounted about 1 m above the ground **[2]**.

3.2.5.2 Obstructions

Pyranometers should be located to avoid obstructions casting a shadow on the sensor at any time. Also, light colored walls and artificial sources of radiation should be avoided **[2]**. Net radiometers should also be located to avoid obstructions to the field of view both upward and downward **[2]**.

3.2.5.3 Siting considerations

Solar radiation measurements should be taken in open areas free of obstructions. The ground cover under a net radiometer should be representative of the general site area. The given application will govern the collection of solar or net radiation data.

3.3 Complex Terrain Locations

For the purposes of this guidance, the term "complex terrain" is intended to mean any site where terrain effects on meteorological measurements may be significant. Terrain effects include aerodynamic wakes, density-driven slope flows, channeling, flow accelerations over the crest of terrain features, etc.; these flows primarily affect wind speed and wind direction measurements, however, temperature and humidity measurements may also be affected. The definition of significance depends on the application; for regulatory dispersion modeling applications, significance is determined by comparing stack-top height and/or an estimated plume height to terrain height - terrain which is below stack-top is classified as simple terrain (see Section 3.2), terrain between stack-top height and plume height is classified as intermediate terrain, and terrain which is above plume height is classified as complex terrain **[1]**.

Vertical gradients and/or discontinuities in the vertical profiles of meteorological variables are often significant in complex terrain. Consequently, measurements of the meteorological variables affecting transport and dispersion of a plume (wind direction, wind speed, and σ_θ) should be made at multiple levels in order to ensure that data used for modeling are representative of conditions at plume level. The ideal arrangement in complex terrain involves siting a tall tower between the source and the terrain feature of concern. The tower should be tall enough to provide measurements at plume level. Other terrain in the area should not significantly affect plume transport in a different manner than that measured by the tower. Since there are not many situations where this ideal can be achieved, a siting decision in complex terrain will almost always be a compromise. Monitoring options in complex terrain range from a single tall tower to multiple tall towers supplemented by data from one or more remote sensing platforms. Other components of the siting decision include determining tower locations, deciding whether or not a tower should be sited on a nearby terrain feature, and determining levels (heights) for monitoring. Careful planning is essential in any siting decision. Since each complex terrain situation has unique features to consider, no specific recommendations can be given to cover all cases. However, the siting process should be essentially the same in all complex terrain situations. Recommended steps in the siting process are as follows:

- Define the variables that are needed for a particular application.
- Develop as much information as possible to define what terrain influences are likely to be important. This should include examination of topographic maps of the area with terrain above physical stack height outlined. Preliminary estimates of plume rise should be made to determine a range of expected plume heights. If any site specific meteorological data are available, they should be analyzed to see what can be learned about the specific

terrain effects on air flow patterns. An evaluation by a meteorologist based on a site visit would also be desirable.

- Examine alternative measurement locations and techniques for required variables. Advantages and disadvantages of each technique/location should be considered, utilizing as a starting point the discussions presented above and elsewhere in this document.
- Optimize network design by balancing advantages and disadvantages.

It is particularly important in complex terrain to consider the end use of each variable separately. Guidance and concerns specific to the measurement of wind speed, wind direction, and temperature difference in complex terrain are discussed in the following sections.

3.3.1 Wind Speed

For use in plume rise calculations, wind speed should be measured at stack top or 100 m, whichever is lower. Ideally, the wind speed sensor should be mounted on a tower located near stack base elevation; however, a tower located on nearby elevated terrain may be used in some circumstances. In this latter case, the higher the tower above terrain the better (i.e. less compression effect); a 10-meter tower generally will not be sufficient. The measurement location should be evaluated for representativeness of both the dilution process and plume rise.

Great care should be taken to ensure that the tower is not sheltered in a closed valley (this would tend to over-estimate the occurrence of stable conditions) or placed in a location that is subject to streamline compression effects (this would tend to underestimate the occurrence of stable conditions). It is not possible to completely avoid both of these concerns. If a single suitable location cannot be found, then alternative approaches, such as multiple towers or a single tall tower supplemented by one or more remote sensing platforms should be considered in consultation with the Regional Office.

3.3.2 Wind Direction

The most important consideration in siting a wind direction sensor in complex terrain is that the measured direction should not be biased in a particular direction that is not experienced by the pollutant plume. For example, instruments on a meteorological tower located at the bottom of a well-defined valley may measure directions that are influenced by channeling or density-driven up-slope or down-slope flows. If the pollutant plume will be affected by the same flows, then the tower site is adequate. Even if the tower is as high as the source's stack, however, appreciable plume rise may take the plume out of the valley influence and the tower's measured wind direction may not be appropriate for the source (i.e., biased away from the source's area of critical impact).

The determination of potential bias in a proposed wind direction measurement is not an easy judgement to make. Quite often the situation is complicated by multiple flow regimes, and the existence of bias is not evident. This potential must be considered, however, and a rationale

developed for the choice of measurement location. Research has indicated that a single wind measurement location/site may not be adequate to define plume transport direction in some situations. While the guidance in this document is concerned primarily with means to obtain a single hourly averaged value of each variable, it may be appropriate to utilize more than one measurement of wind direction to calculate an "effective" plume transport direction for each hour.

3.3.3 Temperature Difference

The requirements of a particular application should be used as a guide in determining how to make measurements of vertical temperature difference in complex terrain. Stable plume rise and the critical dividing streamline height (H_{crit}), which separates flow that tends to move around a hill (below H_{crit}) from flow that tends to pass over a hill (above H_{crit}), are both sensitive to the vertical temperature gradient. The height ranges of interest are from stack top to plume height for the former and from plume height to the top of the terrain feature for the latter. The direct measurement of the complete temperature profile is often desirable but not always practical. The following discussion presents several alternatives for measuring the vertical temperature gradient along with some pros and cons.

Tower measurement: A tower measurement of temperature difference can be used as a representation of the temperature profile. The measurement should be taken between two elevated levels on the tower (e.g. 50 and 100 meters) and should meet the specifications for temperature difference discussed in Section 5.0. A separation of 50 m between the two sensors is preferred. The tower itself could be located at stack base elevation or on elevated terrain: optimum location depends on the height of the plume. Both locations may be subject to radiation effects that may not be experienced by the plume if it is significantly higher than the tower.

The vertical extent of the temperature probe may be partially in and partially out of the surface boundary layer, or may in some situations be entirely contained in the surface boundary layer while the plume may be above the surface boundary layer.

Balloon-based temperature measurements: Temperature profiles taken by balloon-based systems can provide the necessary information but are often not practical for developing a long-term data base. One possible use of balloon-based temperature soundings is in developing better "default" values of the potential temperature gradient on a site-specific basis. A possible approach would be to schedule several periods of intensive soundings during the course of a year and then derive appropriate default values keyed to stability category and wind speed and/or other appropriate variables. The number and scheduling of these intensive periods should be established as part of a sampling protocol.

Deep-layer absolute temperature measurements: If the vertical scale of the situation being modeled is large enough (200 meters or more), it may be acceptable to take the difference between two independent measurements of absolute temperature (i.e., temperature measurements would be taken on two different towers, one at plant site and one on terrain) to serve as a surrogate measurement of the temperature profile. This approach must be justified on a case-by-

case basis, and should be taken only with caution. Its application should be subject to the following limitations:

- Depth of the layer should be 200 meters at a minimum;
- The measurement height on each tower should be at least 60 meters;
- Horizontal separation of the towers should not exceed 2 kilometers;
- No internal boundary layers should be present, such as near shorelines; and
- Temperature profiles developed with the two-tower system should be verified with a program of balloon-based temperature profile measurements.

3.4 Coastal Locations

The unique meteorological conditions associated with local scale land-sea breeze circulations necessitate special considerations. For example, a stably stratified air mass over water can become unstable over land due to changes in roughness and heating encountered during daytime conditions and onshore flow. An unstable thermal internal boundary layer (TIBL) can develop, which can cause rapid downward fumigation of a plume initially released into the stable onshore flow. To provide representative measurements for the entire area of interest, multiple sites would be needed: one site at a shoreline location (to provide 10 m and stack height/plume height wind speed), and additional inland sites perpendicular to the orientation of the shoreline to provide wind speed within the TIBL, and estimates of the TIBL height. Where terrain in the vicinity of the shoreline is complex, measurements at additional locations, such as bluff tops, may also be necessary. Further specific measurement requirements will be dictated by the data input needs of a particular model. A report prepared for the Nuclear Regulatory Commission **[16]** provides a detailed discussion of considerations for conducting meteorological measurement programs at coastal sites.

3.5 Urban Locations

Urban areas are characterized by increased heat flux and surface roughness. These effects, which vary horizontally and vertically within the urban area, alter the wind pattern relative to the outlying rural areas (e.g., average wind speeds are decreased). The close proximity of buildings in downtown urban areas often precludes strict compliance with the previous sensor exposure guidance. For example, it may be necessary to locate instruments on the roof of the tallest available building. In such cases, the measurement height should take into account the proximity of nearby tall buildings and the difference in height between the building (on which the instruments are located) and the other nearby tall buildings.

In general, multiple sites are needed to provide representative measurements in a large urban area. This is especially true for ground-level sources, where low-level, local influences, such as street canyon effects, are important, and for multiple elevated sources scattered over an

urban area. However, due to the limitations of the recommended steady-state guideline models (i.e. they recognize only a single value for each input variable on an hourly basis), and resource and practical constraints, the use of a single site is necessary. At the very least, the single site should be located as close as possible to the source in question.

3.6 Recommendations

Recommendations for siting and exposure of in situ meteorological sensors in simple terrain are as follows:

Sensors for wind speed and wind direction should be located over level, open terrain at a height of 10 m above ground level and at a distance at least ten times the height of nearby obstructions. For elevated releases, additional measurements should be made at stack top or 100 m, whichever is lower. Monitoring requirements for stacks 200 m and above should be determined in consultation with the appropriate EPA Regional Office.

Temperature sensors should be located at 2 m. Probe placement for temperature difference measurements depend on the application. For use in estimating surface layer stability, the measurement should be made between $20z_0$ and $100z_0$; the same recommendation applies to temperature difference measurements for use in estimating the P-G stability category using the solar radiation delta-T method. For use in estimating stable plume rise, temperature difference measurements should be made across the plume rise layer, a minimum separation of 50 m is recommended for this application. Temperature sensors should be shielded to protect them from thermal radiation and any significant heat sources or sinks.

Pyranometers used for measuring incoming (solar) radiation should be located with an unrestricted view of the sky in all directions during all seasons. Sensor height is not critical for pyranometers; a tall platform or rooftop is an acceptable location. Net radiometers should be mounted about 1 m above ground level.

Specific recommendations applicable to siting and exposure of meteorological instruments in complex terrain are not possible. Generally, one should begin the process by conducting a screening analysis to determine, among other things, what terrain features are likely to be important; the screening analysis should also identify potential worse case meteorological conditions. This information should then be used to design a monitoring plan for the specific application.

Special siting considerations also apply to coastal and urban sites. Multiple sites, though often desirable, may not always be possible in these situations. In general, site selection for meteorological monitoring in support of regulatory modeling applications in coastal and urban locations should be conducted in consultation with the appropriate EPA Regional Office.

If the recommendations in this section cannot be achieved, then alternate approaches should be developed in consultation with the appropriate EPA Regional Office. Approval of site

selection for meteorological monitoring should be obtained from the permit granting authority prior to installation of any equipment.

4. METEOROLOGICAL DATA RECORDING

The various meteorological data recording systems available range in complexity from very simple analog or mechanical pulse counter systems to very complex multichannel, automated, microprocessor-based digital data acquisition systems. The function of these systems is to process the electrical output signals from various sensors/transducers and convert them into a form that is usable for display and subsequent analysis. The sensor outputs may come in the form of electrical DC voltages, currents of varying amperage, and/or frequency-varying AC voltages.

4.1 Signal Conditioning

The simpler analog systems utilize the electrical output from a transducer to directly drive the varying pen position on a strip chart. For some variables, such as wind run (total passage of wind) and precipitation, the transducer may produce a binary voltage (either "on" or "off") which is translated into an event mark on the strip chart. Many analog systems and virtually all digital systems require a signal conditioner to translate the transducer output into a form that is suitable for the remainder of the data acquisition system. This translation may include amplifying the signal, buffering the signal (which in effect isolates the transducer from the data acquisition system), or converting a current (amperage) signal into a voltage signal.

4.2 Recording Mechanisms

Both analog and digital systems have a variety of data recording mechanisms or devices available. Analog data may be recorded as continuous traces on a strip chart or as event marks on a chart, as previously described, or as discrete samples on a multi point recorder. The multi point recorder will generally sample each of several variables once every several seconds. The traces for the different variables are differentiated by different colors of ink or by channel numbers printed on the chart next to the trace, or by both. The data collected by digital data acquisition systems may be recorded in hard copy form by a printer or terminal either automatically or upon request, and are generally also recorded on some machine-readable medium such as a magnetic disk storage or tape storage device or a solid-state (nonmagnetic) memory cartridge. Digital systems have several advantages over analog systems in terms of the speed and accuracy of handling the data, and are therefore preferred as the primary recording system. Analog systems may still be useful as a backup to minimize the potential for data loss. For wind speed and wind direction, the analog strip chart records can also provide valuable information to the person responsible for evaluating the data..

4.3 Analog-to-Digital Conversion

A key component of any digital data acquisition system is the analog-to-digital (A/D) converter. The A/D converter translates the analog electrical signal into a binary form that is

suitable for subsequent processing by digital equipment. In most digital data acquisition systems a single A/D converter is used for several data channels through the use of a multiplexer. The rate at which the multiplexer channel switches are opened and closed determines the sampling rates for the channels - all channels need not be sampled at the same the frequency.

4.4 Data Communication

Depending on the type of system, there may be several data communication links. Typically the output signals from the transducers are transmitted to the on-site recording devices directly via hardwire cables. For some applications involving remote locations the data transmission may be accomplished via a microwave telemetering system or perhaps via telephone lines with a dial-up or dedicated line modem system.

4.5 Sampling Rates

The recommended sampling rate for a digital data acquisition system depends on the end use of the data. Substantial evidence and experience suggest that 360 data values evenly spaced during the sampling interval will provide estimates of the standard deviation to within 5 or 10% **[3]**. Estimates of the mean should be based on at least 60 samples to obtain a similar level of accuracy. Sometimes fewer samples will perform as well, but no general guide can be given for identifying these cases before sampling; in some cases, more frequent sampling may be required. If single-pass processing (as described in Section 6.2.1) is used to compute the mean scalar wind direction, then the output from the wind direction sensor (wind vane) should be sampled at least once per second to insure that consecutive values do not differ by more than 180 degrees.

The sampling rate for multi point analog recorders should be at least once per minute. Chart speeds should be selected to permit adequate resolution of the data to achieve the system accuracies recommended in Section 5.1. The recommended sampling rates are minimum values; the accuracy of the data will generally be improved by increasing the sampling rate.

4.6 Recommendations

A microprocessor-based digital data acquisition system should be used as the primary data recording system; analog data recording systems may be used as a backup. Wind speed and wind direction analog recording systems should employ continuous-trace strip-charts; other variables may be recorded on multi point charts. The analog charts used for backup should provide adequate resolution to achieve the system accuracies recommended in Section 5.1.

Estimates of means should be based on at least 60 samples (one sample per minute for an hourly mean). Estimates of the variance should be based on at least 360 samples (six samples per minute for an hourly variance). If single-pass processing is used to calculate the mean scalar wind direction then the output from the wind vane should be sampled at least once per second.

5. SYSTEM PERFORMANCE

5.1 System Accuracies

Accuracy is the amount by which a measured variable deviates from a value accepted as true or standard. Accuracy can be thought of in terms of individual component accuracy or overall system accuracy. For example, the overall accuracy of a wind speed measurement system includes the individual component accuracies of the cup or propeller anemometer, signal conditioner, analog-to-digital converter, and data recorder.

The accuracy of a measurement system can be estimated if the accuracies of the individual components are known. The system accuracy would be the square root of the sum of the squares of the random component accuracies **[17]**. The accuracies recommended for meteorological monitoring systems are listed in Table 5-1. These are stated in terms of overall system accuracies, since it is the data from the measurement system which are used in air quality modeling analyses. Recommended measurement resolutions, i.e., the smallest increments that can be distinguished, are also provided in Table 5-1. These resolutions are considered necessary to maintain the recommended accuracies, and are also required in the case of wind speed and wind direction for computations of standard deviations.

Table 5-1

Recommended System Accuracies and Resolutions

Meteorological Variable	System Accuracy	Measurement Resolution
Wind Speed (horizontal and vertical)	± (0.2 m/s + 5% of observed)	0.1 m/s
Wind Direction (azimuth and elevation)	± 5 degrees	1.0 degree
Ambient Temperature	± 0.5 °C	0.1 °C
Vertical Temperature Difference	± 0.1 °C	0.02 °C
Dew Point Temperature	± 1.5 °C	0.1 °C
Precipitation	± 10% of observed or ± 0.5 mm	0.3 mm
Pressure	± 3 mb (0.3 kPa)	0.5 mb
Solar Radiation	± 5% of observed	10 W/m^2

The recommendations provided in Table 5-1 are applicable to microprocessor-based digital systems (the primary measurement system). For analog systems, used as backup, these recommendations may be relaxed by 50 percent. The averaging times associated with the recommended accuracies correspond to the averaging times associated with the end use of the data (nominally, 1-hour averaging for regulatory modeling applications) and with the audit methods recommended to evaluate system accuracies.

5.2 Response Characteristics of Meteorological Sensors

The response characteristics of the sensors used in meteorological monitoring must be known to ensure that data are appropriate for the intended application. For example, an anemometer designed to endure the rigors experienced on an ocean buoy would not be suitable for monitoring fine scale turbulence in a wind tunnel; the latter application requires a more sensitive instrument with a faster response time (e.g., a sonic anemometer). On the other hand, a sonic anemometer is probably unnecessary if the data are to be used only to calculate hourly averages for use in a dispersion model. Recommended response characteristics for meteorological sensors used in support of air quality dispersion modeling are given in Table 5-2. Definitions of terms commonly associated with instrument response characteristics (including the terms used in Table 5-2) are provided in the following.

Calm. Any average wind speed below the starting threshold of the wind speed or direction sensor, whichever is greater **[4]**.

Damping ratio. The motion of a vane is a damped oscillation and the ratio in which the amplitude of successive swings decreases is independent of wind speed. The damping ratio, h, is the ratio of actual damping to critical damping. If a vane is critically damped, h=l and there is no overshoot in response to sudden changes in wind direction **[18] [19] [20]**.

Delay distance. The length of a column of air that passes a wind vane such that the vane will respond to 50% of a sudden angular change in wind direction **[19]** The delay distance is commonly specified as "50% recovery" using "10° displacement" **[2, 3]**.

Distance constant. The distance constant of a sensor is the length of fluid flow past the sensor required to cause it to respond to 63.2%, i.e., l - l/e, of the increasing step-function change in speed **[19,20]**. Distance constant is a characteristic of cup and propeller (rotational) anemometers.

Range. This is a general term which usually identifies the limits of operation of a sensor, most often within which the accuracy is specified.

Threshold (starting speed). The wind speed at which an anemometer or vane first starts to perform within its specifications20.

Time constant. The time constant is the period that is required for a (temperature) sensor to respond to 63.2%, i.e., l - l/e, of the step-wise change (in temperature). The term is applicable to

any "first-order" sensors, those that respond asymptotically to a step change in the variable being measured, e.g., temperature, pressure, etc.

Table 5-2

Recommended Response Characteristics for Meteorological Sensors

Meteorological Variable	Sensor Specification(s)	
Wind Speed		
Horizontal	Starting Speed:	≤ 0.5 m/s
	Distance Constant:	≤ 5 m
Vertical	Starting Speed:	≤ 0.25 m/s
	Distance Constant:	≤ 5 m
Wind Direction	Starting Speed:	≤ 0.5 m/s @ 10 deg.
	Damping Ratio:	0.4 to 0.7
	Delay Distance:	≤ 5 m
Temperature	Time Constant:	≤ 1 minute
Temperature Difference	Time Constant:	≤ 1 minute
Dew Point Temperature	Time Constant:	≤ 30 minutes
	Range:	-30°C to +30°C
Solar Radiation	Time Constant:	5 sec.
	Operating Range:	-20°C to +40°C
	Spectral Response:	285 nm to 2800 nm

Several publications are available that either contain tabulations of reported sensor response characteristics **[18]**, **[21]** or specify, suggest or recommend values for certain applications **[2, 3, 9]**. Moreover, many manufacturers are now providing this information for the instruments they produce **[21]**. An EPA workshop report on meteorological instrumentation **[3]** expands on these recommendations for certain variables.

Manufacturers of meteorological instruments should provide evidence that the response characteristics of their sensors have been determined according to accepted scientific/technical methods, e.g., ASTM standards **[22]**. Verifying a manufacturer's claims that a meteorological sensor possesses the recommended response characteristics (Table 5-2) is another matter; such verification can accurately be accomplished only in a laboratory setting. In leu of a laboratory test, one must rely on quality assurance performance audit procedures (Section 8.4) - the latter will normally provide assurance of satisfactory performance.

5.3 Data Recovery

5.3.1 Length of Record

The duration of a meteorological monitoring program should be set to ensure that worst-case meteorological conditions are adequately represented in the data base; the minimum duration for most dispersion modeling applications is one year. Recommendations on the length of record for regulatory dispersion modeling as published in The Guideline on Air Quality Models **[1]** are: five years of National Weather Service (NWS) meteorological data or at least one year of site-specific data. Consecutive years from the most recent, readily available 5-year period are preferred.

5.3.2 Completeness Requirement

Regulatory analyses for the short-term ambient air quality standards (1 to 24-hour averaging) involve the sequential application of a dispersion model to every hour in the analysis period (one to five years); such analyses require a meteorological record for every hour in the analysis period. Substitution for missing or invalid data is used to meet this requirement. Applicants in regulatory modeling analyses are allowed to substitute for up to 10 percent of the data; conversely, the meteorological data base must be 90 percent complete (before substitution) in order to be acceptable for use in regulatory dispersion modeling. The following guidance should be followed for purposes of assessing compliance with the 90 percent completeness requirement:

- Lost data due to calibrations or other quality assurance procedures is considered missing data.
- A variable is not considered missing if data for a backup, collocated sensor is available.
- A variable is not considered missing if backup data from an analog system; which meets the applicable response, accuracy and resolution criteria; are available.

- Site specific measurements for use in stability classification are considered equivalent such that the 90 percent requirement applies to stability and not to the measurements (e.g., σ_E and σ_A) used for estimating stability.
- The 90 percent requirement applies on a quarterly basis such that 4 consecutive quarters with 90 percent recovery are required for an acceptable one-year data base.
- The 90 percent requirement applies to each of the variables wind direction, wind speed, stability, and temperature and to the joint recovery of wind direction, wind speed, and stability.

Obtaining the 90 percent goal will necessarily require a commitment to routine preventive maintenance and strict adherence to approved quality assurance procedures (Sections 8.5 and 8.6). Some redundancy in sensors, recorders and data logging systems may also be necessary. With these prerequisites, the 90 percent requirement should be obtainable with available high quality instrumentation. Applicants failing to achieve such are required to continue monitoring until 4 consecutive quarters of acceptable data with 90 percent recovery have been obtained. Substitutions for missing data are allowed, but may not exceed 10 percent of the hours (876 hours per year) in the data base. Substitution procedures are discussed in Section 6.8.

5.4 Recommendations

Recommended system accuracies and resolutions for meteorological data acquisition systems are given in Table 5-l. These requirements apply to the primary measurement system and assume use of a microprocessor digital recording system. If an analog system is used for backup, the values for system accuracy may be relaxed by 50 percent. Recommended response characteristics for meteorological sensors are given in Table 5-2. Manufacturer's documentation verifying an instrument's response characteristics should be reviewed to ensure that verification tests are conducted in a laboratory setting according to accepted scientific/technical methods. Data bases for use in regulatory dispersion modeling applications should be 90 percent complete (before substitution). The 90 percent requirement applies to each meteorological variable separately and to the joint recovery of wind direction, wind speed, and stability. Compliance with the 90 percent requirement should be assessed on a quarterly basis.

6. METEOROLOGICAL DATA PROCESSING

This section provides guidance for processing of meteorological data for use in air quality modeling as follows: Section 6.1 (Averaging and Sampling Strategies), Section 6.2 (Wind Direction, and Wind Speed), Section 6.3 (Temperature), Section 6.4 (Stability), Section 6.5 (Mixing Height), Section 6.6 (Boundary Layer Parameters), Section 6.7 (Use of Airport Data), and Section 6.8 (Treatment of Missing Data). Recommendations are summarized in Section 6.9.

6.1 Averaging and Sampling Strategies

Hourly averaging may be assumed unless stated otherwise; this is in keeping with the averaging time used in most regulatory air quality models. The hourly averaging is associated with the end product of data processing (i.e., the values that are passed on for use in modeling). These hourly averages may be obtained by averaging samples over an entire hour or by averaging a group of shorter period averages. If the hourly average is to be based on shorter period averages, then it is recommended that 15-minute intervals be used. At least two valid 15-minute periods are required to represent the hourly period. The use of shorter period averages in calculating an hourly value has advantages in that it minimizes the effects of meander under light wind conditions in the calculation of the standaard deviation of the wind direction, and it provides more complete information to the meteorologist reviewing the data for periods of transition. It also may allow the recovery of data that might otherwise be lost if only part of the hour is missing.

Sampling strategies vary depending on the variable being measured, the sensor employed, and the accuracy required in the end use of the data. The recommended sampling averaging times for wind speed and wind direction measurements is 1-5 seconds; for temperature and temperature difference measurements, the recommended sample averaging time is 30 seconds **[3]**.

6.2 Wind Direction and Wind Speed

This section provides guidance for processing of in situ measurements of wind direction and wind speed using conventional in situ sensors; i.e., cup and propeller anemometers and wind vanes. Guidance for processing of upper-air wind measurements obtained with remote sensing platforms is provided in Section 9. Recommendations are provided in the following for processing of winds using both scalar computations (Section 6.2.1) and vector computations (Section 6.2.2). Unless indicated otherwise, the methods recommended in Sections 6.2.1 and 6.2.2 employ single-pass processing; these methods facilitate real-time processing of the data as it is collected. Guidance on the treatment of calms is provided in Section 6.2.3. Processing of data to obtain estimates of turbulence parameters is addressed in Section 6.2.4. Guidance on the use of a power-law for extrapolating wind speed with height is provided in Section 6.2.5. The notation for this section is defined in Table 6-2.

Table 6-1

Notation Used in Section 6.2

Observed raw data

u_i	signed magnitude of the horizontal component of the wind vector (i.e., the wind speed)
θ_i	azimuth angle of the wind vector, measured clockwise from north (i.e., the wind direction)
w_i	signed magnitude of the vertical component of the wind vector
ϕ_i	elevation angle of the wind vector (bivane measurement)
N	the number of valid observations

Scalar wind computations

$\overline{u}$, $\overline{U}$	scalar mean wind speed
$\overline{u_h}$	harmonic mean wind speed
$\overline{\theta}$	mean azimuth angle of the wind vector (i.e. the mean wind direction)
$\overline{w}$	mean value of the vertical component of the wind speed
$\overline{\phi}$	mean elevation angle of the wind vector
σ_u	standard deviation of the horizontal component of the wind speed
σ_A, σ_θ	standard deviation of the azimuth angle of the wind
σ_w	standard deviation of the vertical component of the wind speed
σ_E, σ_ϕ	standard deviation of the elevation angle of the wind

Vector wind computations

$\overline{U}_{RV}$	resultant mean wind speed
$\overline{\theta}_{RV}$	resultant mean wind direction
$\overline{\theta}_{UV}$	unit vector mean wind direction
V_e	magnitude of the east-west component of the resultant vector mean wind (positive towards east)
V_n	magnitude of the north-south component of the resultant vector mean wind (positive towards the north)
V_x	magnitude of the east-west component of the unit vector mean wind
V_y	magnitude of the north-south component of the unit vector mean wind
x,y,z	standard right-hand-rule coordinate system with x-axis aligned towards the east.

6.2.1 Scalar Computations

The scalar mean wind speed is:

$$\bar{u} = \frac{1}{N}\sum_{1}^{N} u_i \qquad \textbf{(6.2.1)}$$

The harmonic mean wind speed is:

$$\overline{u_h} = \left(\frac{1}{N}\sum_{1}^{N}\frac{1}{u_i}\right)^{-1} \qquad \textbf{(6.2.2)}$$

The standard deviation of the horizontal component of the wind speed is:

$$\sigma_u = \left[\frac{1}{N}\left\{\sum_{1}^{N} u_i^2 - \frac{1}{N}\left(\sum_{1}^{N} u_i\right)^2\right\}\right]^{1/2} \qquad \textbf{(6.2.3)}$$

The wind direction is a circular function with values between l and 360 degrees. The wind direction discontinuity at the beginning/end of the scale requires special processing to compute a valid mean value. A single-pass procedure developed by Mitsuta and documented in reference **[23]** is recommended. The method assumes that the difference between successive wind direction samples is less than 180 degrees; to ensure such, a sampling rate of once per second or greater should be used (see Section 6.2.4). Using the Mitsuta method, the scalar mean wind direction is computed as:

$$\bar{\theta} = \frac{1}{N}\sum_{1}^{N} D_i \qquad \textbf{(6.2.4)}$$

where $D_i = \theta_i$; for I = 1

$D_i = D_{i-1} + \delta_i + 360$; for $\delta_i < -180$ and I > 1

$D_i = D_{i-1} + \delta_i$; for $|\delta_i| < 180$ and I > 1

$D_i = D_{i-1} + \delta_i - 360$; for $\delta_i > 180$ and I > 1

D_i is undefined for $\delta_i = 180$ and I > 1

$\delta_i = \theta_i - D_{i-1}$; for I > 1

θ_i is the azimuth angle of the wind vane for the ith sample.

The following notes/cautions apply to the determination of the scalar mean wind direction using Equation. 6.2.4:

- If the result is less than zero or greater than 360, increments of 360 degrees should be added or subtracted, as appropriate, until the result is between zero and 360 degrees.
- Erroneous results may be obtained if this procedure is used to post-process sub-hourly averages to obtain an hourly average. This is because there can be no guarantee that the difference between successive sub-hourly averages will be less than 180 degrees.

The scalar mean wind direction, as defined in Equation. 6.2.4, retains the essential statistical property of a mean value, namely that the deviations from the mean must sum to zero:

$$\sum (\theta_i - \bar{\theta}) = 0 \qquad \textbf{(6.2.5)}$$

By definition, the same mean value must be used in the calculation of the variance of the wind direction and, likewise, the standard deviation (the square root of the variance). The variance of the wind direction is given by:

$$\sigma_\theta^2 = \frac{1}{N} \sum (\theta_i - \bar{\theta})^2 \qquad \textbf{(6.2.6)}$$

The standard deviation of the wind direction using the Mitsuta method is given by:

$$\sigma_A = \sigma_\theta = \left[\frac{1}{N} \left\{ \sum_1^N D_i^2 - \frac{1}{N} \left(\sum_1^N D_i \right)^2 \right\} \right]^{1/2} \qquad \textbf{(6.2.7)}$$

Cases may arise in which the sampling rate is insufficient to assure that differences between successive wind direction samples are less than 180 degrees. In such cases, approximation formulas may be used for computing the standard deviation of the wind direction. Mardia **[24]** shows that a suitable estimate of the standard deviation (in radian measure) is:

$$\sigma_A = \sigma_\theta = \left[-2 \ln(R) \right]^{1/2} \qquad \textbf{(6.2.8)}$$

where

$$R = (Sa^2 + Ca^2)^{1/2}$$

$$Sa = \frac{1}{N} \sum_1^N \sin(\theta_i)$$

$$Ca = \frac{1}{N} \sum_1^N \cos(\theta_i)$$

Several methods for calculating the standard deviation of the wind direction were evaluated by Turner **[25]**; a method developed by Yamartino **[26]** was found to provide excellent results for most cases. The Yamartino method is given in the following:

$$\sigma_A = \sigma_\theta = \arcsin(\epsilon)\ [1. + 0.1547\ \epsilon^3] \qquad \textbf{(6.2.9)}$$

where

$$\epsilon = \left[1. - \left(\overline{\sin(\theta_i)}^{\,2} + \overline{\cos(\theta_i)}^{\,2} \right)\right]^{1/2}$$

Note that hourly σ_θ values computed using 6.2.7, 6.2.8, or 6.2.9 may be inflated by contributions from long period oscillations associated with light wind speed conditions (e.g., wind meander). To minimize the effects of wind meander, the hourly σ_θ (for use e.g., in stability determinations - see Section 6.4.4.4) should be calculated based on four 15-minute values averaged as follows:

$$\sigma_\theta(1-hr) = \left[\left\{(\sigma_{\theta_1})^2 + (\sigma_{\theta_2})^2 + (\sigma_{\theta_3})^2 + (\sigma_{\theta_4})^2\right\} /4 \right]^{1/2} \qquad \textbf{(6.2.10)}$$

The standard deviation of the vertical component of the wind speed is:

$$\sigma_w = \left[\frac{1}{N}\left\{\sum_1^N w_i^2 - \frac{1}{N}\left(\sum_1^N w_i\right)^2\right\}\right]^{1/2} \qquad \textbf{(6.2.11)}$$

Similarly, the standard deviation of the elevation angle of the wind vector is:

$$\sigma_E = \sigma_\phi = \left[\frac{1}{N}\left\{\sum_1^N \phi_i^2 - \frac{1}{N}\left(\sum_1^N \phi_i\right)^2\right\}\right]^{1/2} \qquad \textbf{(6.2.12)}$$

Equation 6.2.12 is provided for completeness only. The bivane, which is used to measure the elevation angle of the wind, is regarded as a research grade instrument and is not recommended for routine monitoring applications. See Section 6.2.3 for recommendations on estimating σ_ϕ.

6.2.2 Vector Computations

From the sequence of N observations of θ_i and u_i, the mean east-west, V_e, and north-south, V_n, components of the wind are:

$$V_e = -\frac{1}{N}\sum u_i \sin(\theta_i) \qquad \textbf{(6.2.13)}$$

$$V_n = -\frac{1}{N} \sum u_i \cos(\theta_i) \qquad \textbf{(6.2.14)}$$

The resultant mean wind speed and direction are:

$$\overline{U}_{RV} = (V_e^2 + V_n^2)^{1/2} \qquad \textbf{(6.2.15)}$$

$$\overline{\theta}_{RV} = ArcTan\ (V_e/V_n) + FLOW \qquad \textbf{(6.2.16)}$$

where

$$FLOW \begin{array}{ll} = +180; & for\ ArcTan(V_e/V_n) < 180 \\ = -180; & for\ ArcTan(V_e/V_n) > 180 \end{array}$$

Equation 6.2.16 assumes the angle returned by the ArcTan function is in degrees. This is not always the case and depends on the computer processor. Also, the ArcTan function can be performed several ways. For instance, in FORTRAN either of the following forms could be used:

$$ATAN(V_e/V_n)$$

or $$ATAN2(V_e, V_n).$$

The ATAN2 form avoids the extra checks needed to insure that V_n is nonzero, and is defined over a full 360 degree range.

The unit vector approach to computing mean wind direction is similar to the vector mean described above except that the east-west and north-south components are not weighted by the wind speed. Using the unit vector approach, equations 6.2.13 and 6.2.14 become:

$$V_x = -\frac{1}{N} \sum Sin\ \theta_i \qquad \textbf{(6.2.17)}$$

$$V_y = -\frac{1}{N} \sum Cos\theta_i \qquad \textbf{(6.2.18)}$$

The unit vector mean wind direction is:

$$\bar{\theta}_{UV} = ArcTan\ (V_x/V_y) + FLOW \qquad \textbf{(6.2.19)}$$

where

$$FLOW \begin{array}{l} = +180; \quad for\ ArcTan(V_x/V_y) < 180 \\ = -180; \quad for\ ArcTan(V_x/V_y) > 180 \end{array}$$

In general, the unit vector result will be comparable to the scalar average wind direction, and may be used to model plume transport.

6.2.3 Treatment of Calms

Calms, periods with little or no air movement, require special consideration in air quality evaluations; one of the more important considerations involves model selection. If the limiting air quality conditions are associated with calms, then a non-steady-state model, such as CALPUFF **[27]**, should be used. The use of a time varying 3-dimensional flow field in this model enables one to simulate conditions which are not applicable to steady-state models; e.g., recirculations and variable trajectories. Guidance for preparing meteorological data for use in CALPUFF is provided in the user's guide to the meteorological processor for this model **[28]**.

Steady-state models may be used for regulatory modeling applications if calms are not expected to be limiting for air quality. Calms require special treatment in such applications to avoid division by zero in the steady-state dispersion algorithm. EPA recommended steady-state models such as ISCST accomplish this with routines that nullify concentrations estimates for calm conditions and adjust short-term and annual average concentrations as appropriate. The EPA CALMPRO **[29]** program post-processes model output to achieve the same effect for certain models lacking this built-in feature. For similar reasons, to avoid unrealistically high concentration estimates at low wind speeds (below the values used in validations of these models - about 1 m/s) EPA recommends that wind speeds less than 1 m/s be reset to 1 m/s for use in steady-state dispersion models; the unaltered data should be retained for use in non-steady-state modeling applications. Calms should be identified in processed data files by flagging the appropriate records; user's guides for the model being used should be consulted for model specific flagging conventions.

For the purposes of this guidance and for the objective determination of calm conditions applicable to in situ monitoring, a calm occurs when the wind speed is below the starting threshold of the anemometer or vane, whichever is greater. For site-specific monitoring (using the recommended thresholds for wind direction and wind speed given in Table 5-2) a calm occurs when the wind speed is below 0.5 m/s. One should be aware that the frequency of calms are typically higher for NWS data bases because the sensors used to measure wind speed and wind direction have a higher threshold - typically 2 kts (1 m/s) - see Section 6.7.

6.2.4 Turbulence

6.2.4.1 Estimating σ_E from σ_w

Applications requiring the standard deviation of the elevation angle of the wind (e.g., see Section 6.4.4) should use the following approximation:

$$\sigma_E = \sigma_w/\bar{u} \qquad \textbf{(6.2.20)}$$

where σ_E is the standard deviation of the elevation angle of the wind (radians)

σ_w is the standard deviation of the vertical component of the wind speed (m/s)

$\bar{u}$ is the scalar mean wind speed (m/s).

Weber et. al. **[30]** reported good performance for an evaluation using data measured at the Savannah River Laboratory for wind speeds greater than 2 m/s. In a similar study, Deihl **[31]** reported satisfactory performance for wind speeds greater than 2 m/s. In the Deihl study, the performance varied depending on the overall turbulence intensity. It is concluded from these studies that σ_E is best approximated by $\sigma_w/\bar{u}$ when wind speeds are greater than 2 m/s, and σ_E is greater than 3 degrees.

6.2.5 Wind Speed Profiles

Dispersion models recommended for regulatory applications employ algorithms for extrapolating the input wind speed to the stack-top height of the source being modeled; the wind speed at stack-top is used for calculating transport and dilution. This section provides guidance for implementing these extrapolations using default parameters and recommends procedures for developing site specific parameters for use in place of the defaults.

For convenience, in non-complex terrain up to a height of about 200 m above ground level, it is assumed that the wind profile is reasonably well approximated as a power-law of the form:

$$U_z = U_r(Z/Z_r)^p \qquad \textbf{(6.2.21)}$$

where U_z = the scalar mean wind speed at height z above ground level

U_r = the scalar mean wind speed at some reference height Z_r, typically 10 m

p = the power-law exponent.

The power-law exponent for wind speed typically varies from about 0.1 on a sunny afternoon to about 0.6 during a cloudless night. The larger the power-law exponent the larger the vertical gradient in the wind speed. Although the power-law is a useful engineering approximation of the average wind speed profile, actual profiles will deviate from this relationship.

Site-specific values of the power-law exponent may be determined for sites with two levels of wind data by solving Equation (6.2.20) for p:

$$p = \frac{\ln(U) - \ln(U_r)}{\ln(Z) - \ln(Z_r)} \qquad \textbf{(6.2.21)}$$

As discussed by Irwin **[32]**, wind profile power-law exponents are a function of stability, surface roughness and the height range over which they are determined. Hence, power-law exponents determined using two or more levels of wind measurements should be stratified by stability and surface roughness. Surface roughness may vary as a function of wind azimuth and season of the year (see Section 6.4.2). If such variations occur, this would require azimuth and season dependent determination of the wind profile power-law exponents. The power-law exponents are most applicable within the height range and season of the year used in their determination. Use of these wind profile power-law exponents for estimating the wind at levels above this height range or to other seasons should only be done with caution. The default values used in regulatory models are given in Table 6-2.

Table 6-2

Recommended Power-law Exponents for Urban and Rural Wind Profiles

Stability Class	Urban Exponent	Rural Exponent
A	0.15	0.07
B	0.15	0.07
C	0.20	0.10
D	0.25	0.15
E	0.30	0.35
F	0.30	0.55

The following discussion presents a method for determining at what levels to specify the wind speed on a multi-level tower to best represent the wind speed profile in the vertical. The problem can be stated as, what is the percentage error resulting from using a linear interpolation over a height interval (between measurement levels), given a specified value for the power-law

exponent. Although the focus is on wind speed, the results are equally applicable to profiles of other meteorological variables that can be approximated by power laws.

Let U_l represent the wind speed found by linear interpolation and U the "correct" wind speed. Then the fractional error is:

$$FE = (U_l - U)/U \tag{6.2.22}$$

The fractional error will vary from zero at both the upper, Z_u, and lower, Z_l, bounds of the height interval, to a maximum at some intervening height, Z_m. If the wind profile follows a power law, the maximum fractional error and the height at which it occurs are:

$$FE_{max} = \frac{(Z_l/Z_r)^p - (Z_m/Z_r)^p + A(Z_m - Z_l)/(Z_u - Z_l)}{(Z_m/Z_r)^p} \tag{6.2.23}$$

where

$$A = (Z_u/Z_r)^p - (Z_l/Z_r)^p$$

and

$$Z_m = [pZ_l/(p-1)] - [p/(p-1)]\ (Z_l/Z_r)^p\ (Z_u - Z_l)/A$$

As an example, assume p equals 0.34 and the reference height, Z_r, is 10 m. Then for the following height intervals, the maximum percentage error and the height at which it occurs are:

Interval (m)	Maximum Error (%)	Height of Max Error (m)
2 - 10	-6.83	4.6
10 - 25	-2.31	16.0
25 - 50	-1.33	35.6
50 - 100	-1.33	71.2

As expected, the larger errors occur for the lower heights where the wind speed changes most rapidly with height. Thus, sensors should be spaced more closely together in the lower heights to best approximate the actual profile. Since the power-law is only an approximation of the actual profile, errors can occur that are larger than those estimated using (6.2.22). Even with this limitation, the methodology is useful for determining the optimum heights to place a limited number of wind sensors. The height Z_m represents the optimum height to place a third sensor given the location of the two surrounding sensors.

6.3 Temperature

Temperature is used in calculations to determine plume rise (Section 6.3.1), mixing height (Section 6.5), and various surface-layer parameters (Section 6.6). Unless indicated otherwise, ambient temperature measurements should be used in these calculations. Although not essential, the ambient temperature may also be used for consistency checking in QA procedures. Applications of vertical temperature gradient measurements are discussed in Section 6.3.2.

6.3.1 Use in Plume-Rise Estimates

Temperature is used in calculating the initial buoyancy flux in plume rise calculations as follows:

$$F = g(T_p - T_e)V/T_p \qquad \textbf{(6.3.1)}$$

where the subscripts p and e indicate the plume and environmental values, respectively, and V is the volume flux **[13]**.

6.3.2 Vertical Temperature Gradient

Vertical temperature gradient measurements are used for classifying stability in the surface layer, in various algorithms for calculating surface scaling parameters, and in plume rise equations for stable conditions. For all of these applications the relative accuracy and resolution of the thermometers are of critical importance. Recommended heights for temperature gradient measurements in the surface layer are 2 m and 10 m. For use in estimating plume rise in stable conditions, the vertical temperature gradient should be determined using measurements across the plume rise layer; a minimum height separation of 50 m is recommended for this application.

6.4 Stability

Stability typing is employed in air quality dispersion modeling to facilitate estimates of lateral and vertical dispersion parameters [e.g., the standard deviation of plume concentration in the lateral (σ_y) and vertical (σ_z)] used in Gaussian plume models. The preferred stability typing scheme, recommended for use in regulatory air quality modeling applications is the scheme proposed in an article by Pasquill in 1961 **[33]**; the dispersion parameters associated with this scheme [often referred to as the Pasquill-Gifford (P-G) sigma curves] are used by default in most of the EPA recommended Gaussian dispersion models.

Table 6-3 provides a key to the Pasquill stability categories as originally defined; though impractical for routine application, the original scheme provided a basis for much of the

developmental work in dispersion modeling. For routine applications using the P-G sigmas, the Pasquill stability category (hereafter referred to as the P-G stability category) should be calculated using the method developed by Turner **[34]**; Turner's method is described in Section 6.4.1. Subsequent sections describe alternative methods for estimating the P-G stability category when representative cloud cover and ceiling data are not available. These include a radiation-based method which uses measurements of solar radiation during the day and delta-T at night (Section 6.4.2) and turbulence-based methods which use wind fluctuation statistics (Sections 6.4.3 and 6.4.4). Procedures for the latter are based on the technical note published by Irwin in 1980 **[35]**; user's are referred to the technical note for background on the estimation of P-G stability categories.

Table 6-3

Key to the Pasquill Stability Categories

	Daytime Insolation			Nighttime cloud cover	
Surface wind speed (m/s)	Strong	Moderate	Slight	Thinly overcast or ≥4/8 low cloud	≤ 3/8
< 2	A	A - B	B	-	-
2 - 3	A - B	B	C	E	F
3 - 5	B	B - C	C	D	E
5 - 6	C	C - D	D	D	D
> 6	C	D	D	D	D

Strong insolation corresponds to sunny, midday, midsummer conditions in England; slight insolation corresponds to similar conditions in midwinter. Night refers to the period from one hour before sunset to one hour after sunrise. The neutral category, D, should be used regardless of wind speed, for overcast conditions during day or night.

6.4.1 Turner's method

Turner **[34]** presented a method for determining P-G stability categories from data that are routinely collected at National Weather Service (NWS) stations. The method estimates the effects of net radiation on stability from solar altitude (a function of time of day and time of year), total cloud cover, and ceiling height. Table 6-4 gives the stability class (1=A, 2=B,...) as a function of wind speed and net radiation index. Since the method was developed for use with NWS data, the wind speed is given in knots. The net radiation index is related to the solar altitude (Table 6-5) and is determined from the procedure described in Table 6-6. Solar altitude can be determined from the Smithsonian Meteorological Tables **[36]**. For EPA regulatory

modeling applications, stability categories 6 and 7 (F and G) are combined and considered category 6.

Table 6-4

Turner's Key to the P-G Stability Categories

Wind Speed		Net Radiation Index						
(knots)	(m/s)	4	3	2	1	0	-1	-2
0,1	0 - 0.7	1	1	2	3	4	6	7
2,3	0.8 - 1.8	1	2	2	3	4	6	7
4,5	1.9 - 2.8	1	2	3	4	4	5	6
6	2.9 - 3.3	2	2	3	4	4	5	6
7	3.4 - 3.8	2	2	3	4	4	4	5
8,9	3.9 - 4.8	2	3	3	4	4	4	5
10	4.9 - 5.4	3	3	4	4	4	4	5
11	5.5 - 5.9	3	3	4	4	4	4	4
≥ 12	≥ 6.0	3	4	4	4	4	4	4

Table 6-5

Insolation Class as a Function of Solar Altitude

Solar Altitude Φ (degrees)	Insolation	Insolation Class Number
$60 < \Phi$	strong	4
$35 < \Phi \leq 60$	moderate	3
$15 < \Phi \leq 35$	slight	2
$\Phi \leq 15$	weak	1

Table 6-6

Procedure for Determining the Net Radiation Index

1. If the total cloud[1] cover is 10/10 and the ceiling is less than 7000 feet, use net radiation index equal to 0 (whether day or night).

2. For nighttime: (from one hour before sunset to one hour after sunrise):
   - (a) If total cloud cover $\leq$ 4/10, use net radiation index equal to -2.
   - (b) If total cloud cover > 4/10, use net radiation index equal to -1.

3. For daytime:
   - (a) Determine the insolation class number as a function of solar altitude from Table 6-5.
   - (b) If total cloud cover $\leq$5/10, use the net radiation index in Table 6-4 corresponding to the isolation class number.
   - © If cloud cover >5/10, modify the insolation class number using the following six steps.
     - (l) Ceiling <7000 ft, subtract 2.
     - (2) Ceiling $\geq$7000 ft but <16000 ft, subtract 1.
     - (3) total cloud cover equal 10/10, subtract 1. (This will only apply to ceilings $\geq$7000 ft since cases with 10/10 coverage below 7000 ft are considered in item 1 above.)
     - (4) If insolation class number has not been modified by steps (1), (2), or (3) above, assume modified class number equal to insolation class number.
     - (5) If modified insolation class number is less than 1, let it equal 1.
     - (6) Use the net radiation index in Table 6-4 corresponding to the modified insolation class number.

[1] *Although Turner indicates total cloud cover, opaque cloud cover is implied by Pasquill and is preferred; EPA recommended meteorological processors, MPRM and PCRAMMET, will accept either.*

6.4.2 Solar radiation/delta-T (SRDT) method

The solar radiation/delta-T (SRDT) method retains the basic structure and rationale of Turner's method while obviating the need for observations of cloud cover and ceiling. The method, outlined in Table 6-7, uses the surface layer wind speed (measured at or near 10 m) in combination with measurements of total solar radiation during the day and a low-level vertical temperature difference (ΔT) at night (see Section 3.1.2.1 for guidance on probe placement for measurement of the surface layer ΔT). The method is based on Bowen et al. **[37]** with modifications as necessary to retain as much as possible of the structure of Turner's method.

Table 6-7

Key to Solar Radiation Delta-T (SRDT) Method for Estimating

Pasquill-Gifford (P-G) Stability Categories

DAYTIME

	Solar Radiation (W/m^2)			
Wind Speed (m/s)	≥ 925	925 - 675	675 - 175	< 175
< 2	A	A	B	D
2 - 3	A	B	C	D
3 - 5	B	B	C	D
5 - 6	C	C	D	D
≥ 6	C	D	D	D

NIGHTTIME

	Vertical Temperature Gradient	
Wind Speed (m/s)	< 0	≥ 0
< 2.0	E	F
2.0 - 2.5	D	E
≥ 2.5	D	D

6.4.3 σ_E method

The σ_E method (Tables 6-8a and 6-8b) is a turbulence-based method which uses the standard deviation of the elevation angle of the wind in combination with the scalar mean wind speed.

The criteria in Table 6-8a and Table 6-8b are for data collected at 10m and a roughness length of 15 cm. Wind speed and direction data collected within the height range from $20z_0$ to $100z_0$ should be used. For sites with very low roughness, these criteria are slightly modified. The lower bound of measurement height should never be less than 1.0 m; the upper bound should never be less than 10 m. To obtain 1-hour averages, the recommended sampling duration is 15 minutes, but it should be at least 3 minutes and may be as long as 60 minutes. The relationships employed in the estimation methods assume conditions are steady state. This is more easily achieved if the sampling duration is less than 30 minutes.

Table 6-8a

Vertical Turbulence[a] Criteria for Initial Estimate of Pasquill-Gifford (P-G) Stability Category. For use with Table 6-7b.

Initial estimate of P-G stability category	Standard deviation of wind elevation angle σ_E (degrees)
A	$11.5 \leq \sigma_E$
B	$10.0 \leq \sigma_E < 11.5$
C	$7.8 \leq \sigma_E < 10.0$
D	$5.0 \leq \sigma_E < 7.8$
E	$2.4 \leq \sigma_E < 5.0$
F	$\sigma_E < 2.4$

[a] As indicated by the standard deviation of the elevation angle of the wind vector, σ_ϕ. Sigma-E and σ_E are aliases for σ_ϕ.

Table 6-8b

Wind Speed Adjustments for Determining Final Estimate of P-G Stability Category from σ_E. For use with Table 6-8a.

Initial estimate of P-G Category		10-meter wind speed (m/s)	Final estimate of P-G Category
Daytime	A	$u < 3$	A
	A	$3 \leq u < 4$	B
	A	$4 \leq u < 6$	C
	A	$6 \leq u$	D
	B	$u < 4$	B
	B	$4 \leq u < 6$	C
	B	$6 \leq u$	D
	C	$u < 6$	C
	C	$6 \leq u$	D
	D, E, or F	ANY	D
Nighttime	A	ANY	D
	B	ANY	D
	C	ANY	D
	D	ANY	D
	E	$u < 5$	E
	E	$5 \leq u$	D
	F	$u < 3$	F
	F	$3 \leq u < 5$	E
	F	$5 \leq u$	D

If the site roughness length is other than 15 cm, the category boundaries listed in Table 6-8a may need to be adjusted. As an initial adjustment, multiply the Table 6-8a values by:

$$(z_o/15)^{0.2}$$

where z_o is the site roughness in centimeters. This factor, while theoretically sound, has not had widespread testing. It is likely to be a useful adjustment for cases when z_o is greater than 15 cm. It is yet problematical whether the adjustment is as useful for cases when z_o is less than 15 cm.

If the measurement height is other than 10 m, the category boundaries listed in Table 6-8a will need to be adjusted. As an initial adjustment, multiply the lower bound values by:

$$\mathbf{(Z/10)^{P_\phi}}$$

where Z is the measurement height in meters. The exponent P_ϕ is a function of the P-G stability category with values as follows:

P-G Stability	P_ϕ
A	0.02
B	0.04
C	0.01
D	-0.14
E	-0.31

The above suggestions summarize the results of several studies conducted in fairly ideal circumstances. It is anticipated that readers of this document are often faced with conducting analyses in less than ideal circumstances. Therefore, before trusting the Pasquill category estimates, the results should be spot checked. This can easily be accomplished. Choose cloudless days. In mid-afternoon during a sunny day, categories A and B should occur. During the few hours just before sunrise, categories E and F should occur. The bias, if any, in the turbulence criteria will quickly be revealed through such comparisons. Minor adjustments to the category boundaries will likely be needed to tailor the turbulence criteria to the particular site characteristics, and should be made in consultation with the reviewing agency.

6.4.4 σ_A method

The σ_A method (Tables 6-9a and 6-9b) is a turbulence-based method which uses the standard deviation of the wind direction in combination with the scalar mean wind speed. The criteria in Table 6-9a and Table 6-9b are for data collected at 10 m and a roughness length of 15 cm. Wind speed and direction data collected within the height range from $20z_o$ to $100z_o$ should be used. For sites with very low roughness, these criteria are slightly modified. The lower bound

measurement height should never be less than 1 m. The upper bound should never be less than 10 m. To obtain 1-hour averages, the recommended sampling duration is 15 minutes, but it should be at least 3 minutes and may be as long as 60 minutes. The relationships employed in the estimation methods assume conditions are steady state. This is more easily achieved if the sampling duration is less than 30 minutes. To minimize the effects of wind meander, the 1-hour σ_A is defined using 15-minute values (see Equation. 6.2.10).

Table 6-9a

Lateral Turbulence[a] Criteria for Initial Estimate of Pasquill-Gifford (P-G) Stability Category. For use with Table 6-8b.

Initial estimate of P-G stability category	Standard deviation of wind azimuth angle σ_A
A	$22.5 \leq \sigma_A$
B	$17.5 \leq \sigma_A < 22.5$
C	$12.5 \leq \sigma_A < 17.5$
D	$7.5 \leq \sigma_A < 12.5$
E	$3.8 \leq \sigma_A < 7.5$
F	$\sigma_A < 3.8$

[a] As indicated by the standard deviation of the azimuth angle of the wind vector, σ_θ. Sigma-A, Sigma-Theta, and σ_A are aliases for σ_θ.

Table 6-9b

Wind Speed Adjustments for Determining Final Estimate of P-G Stability Category from σ_A. For use with Table 6-9a.

Initial estimate of P-G Category		10-meter wind speed (m/s)	Final estimate of P-G Category
Daytime	A	$u < 3$	A
	A	$3 \leq u < 4$	B
	A	$4 \leq u < 6$	C
	A	$6 \leq u$	D
	B	$u < 4$	B
	B	$4 \leq u < 6$	C
	B	$6 \leq u$	D
	C	$u < 6$	C
	C	$6 \leq u$	D
	D, E, or F	ANY	D
Nighttime	A	$u < 2.9$	F
	A	$2.9 \leq u < 3.6$	E
	A	$3.6 \leq u$	D
	B	$u < 2.4$	F
	B	$2.4 \leq u < 3.0$	E
	B	$3.0 \leq u$	D
	C	$u < 2.4$	E
	C	$2.4 \leq u$	D
	D	ANY	D
	E	$u < 5$	E
	E	$5 \leq u$	D
	E		
	F	$u < 3$	F
	F	$3 \leq u < 5$	E
	F	$5 \leq u$	D

.

If the site roughness length is other than 15 cm, the category boundaries listed in Table 6-9a may need adjustment. As an initial adjustment, multiply the values listed by:

$$(z_o/15)^{0.2}$$

where z_o is the site roughness in centimeters. This factor, while theoretically sound, has not had widespread testing. It is likely to be a useful adjustment for cases when z_o is greater than 15 cm. It is yet problematical whether the adjustment is as useful for cases when z_o is less than 15 cm.

If the measurement height is other than 10 m, the category boundaries listed in Table 6-9a will need adjustment. As an initial adjustment, multiply the lower bound values listed by:

$$\mathbf{(Z/10)^{P_\theta}}$$

where Z is the measurement height in meters.

The exponent P_θ is a function of the P-G stability category with values as follows:

P-G Stability	P_θ
A	-0.06
B	-0.15
C	-0.17
D	-0.23
E	-0.38

The above suggestions summarize the results of several studies conducted in fairly ideal circumstances. It is anticipated that readers of this document are often faced with conducting analyses in less than ideal circumstances. Therefore, before trusting the Pasquill category estimates, the results should be spot checked. This can easily be accomplished. Choose cloudless days. In mid-afternoon during a sunny day, categories A and B should occur. During the few hours just before sunrise, categories E and F should occur. The bias, if any, in the turbulence criteria will quickly be revealed through such comparisons. Minor adjustments to the category boundaries will likely be needed to tailor the turbulence criteria to the particular site characteristics, and should be made in consultation with the reviewing agency.

6.4.5 Accuracy of stability category estimates

By virtue of its historic precedence and widespread use, EPA considers Turner's method **[34]** to be the benchmark procedure for determining P-G stability. Evaluations performed in developing the SRDT method indicate that this method identifies the same P-G stability category

as Turner's method (Section 6.4.1) about 60 percent of the time and is within one category about 90 percent of the time (EPA, 1994) **[38]**. Results are not available comparing the performance of the σ_A and σ_E methods outlined above in this section. However, there are comparison results for similar methods. From these studies, it is concluded that the methods will estimate the same stability category about 50 percent of the time and will be within one category about 90 percent of the time. Readers are cautioned that adjustment of the turbulence criteria resulting from spot checks is necessary to achieve this performance. For additional information on stability classification using wind fluctuation statistics, see references **[39]**, **[40]**, **[41]**, and **[42]**.

6.5 Mixing Height

For the purposes of this guidance, mixing height is defined as the height of the layer adjacent to the ground over which an emitted or entrained inert non-buoyant tracer will be mixed (by turbulence) within a time scale of about one hour or less **[43]**. Taken literally, the definition means that routine monitoring of the mixing height is generally impractical. For routine application, alternative methods are recommended for estimating mixing heights based on readily available data.

The Holzworth method **[44]** is recommended for use when representative NWS upper-air data are available. This procedure relies on the general theoretical principle that the lapse rate is roughly dry adiabatic (no change in potential temperature with height) in a well-mixed daytime convective boundary layer (CBL); the Holzworth method is described in Section 6.5.1. Other alternatives include using estimates of mixing heights provided in CBL model output (Weil and Brower **[45]**; Paine **[46]**) and mixing heights derived from remote sensing measurements of turbulence or turbulence related parameters; the latter are discussed in Section 9.1.1.

6.5.1 The Holzworth Method

The Holzworth method **[44]** provides twice-per-day (morning and afternoon) mixing heights based on calculations using routine NWS upper-air data. The morning mixing height is calculated as the height above ground at which the dry adiabatic extension of the morning minimum surface temperature plus 5°C intersects the vertical temperature profile observed at 1200 Greenwich Mean Time (GMT). The minimum temperature is determined from the regular hourly airways reports from 0200 through 0600 Local Standard Time (LST). The “plus 5°C “ was intended to allow for the effects of the nocturnal and early morning urban heat island since NWS upper-air stations are generally located in rural or suburban surroundings. However, it can also be interpreted as a way to include the effects of some surface heating shortly after sunrise. Thus, the time of the urban morning mixing height coincides approximately with that of the typical diurnal maximum concentration of slow-reacting pollutants in many cities, occurring around the morning commuter rush hours.

The afternoon mixing height is calculated in the same way, except that the maximum surface temperature observed from 1200 through 1600 LST is used. Urban-rural differences of maximum surface temperature are assumed negligible. The typical time of the afternoon mixing height may be considered to coincide approximately with the usual mid-afternoon minimum concentration of slow-reacting urban pollutants.

Hourly mixing heights, for use in regulatory dispersion modeling, are interpolated from these twice per day estimates. The recommended interpolation procedure is provided in the user’s guide for the Industrial Source Complex (ISC) dispersion model **[47]**.

6.6 Boundary Layer Parameters

This section provides recommendations for monitoring in support of air quality dispersion models which incorporate boundary layer scaling techniques. The applicability of these techniques is particularly sensitive to the measurement heights for temperature and wind speed; the recommendations for monitoring, given in Section 6.6.4, consequently, focus on the placement of the temperature and wind speed sensors. A brief outline of boundary layer theory, given in the following, provides necessary context for these recommendations. The references for this section **[48]**, **[49]**, **[50]**, **[51]**, **[52]**, **[53]**, **[54]**, **[55]**, **[56]**, **[57]**, **[58]**, **[59]** provide more detailed information on boundary layer theory.

The Atmospheric Boundary Layer (ABL) can be defined as the lower layer of the atmosphere, where processes which contribute to the production or destruction of turbulence are significant; it is comprised of two layers, a lower surface layer, and a so-called "mixed" upper layer. The height of the ABL during daytime roughly coincides with the height to which pollutants are mixed (the mixing height, Section 6.5). During night-time stable conditions, the mixing height (h) is an order of magnitude smaller than the maximum daytime value over land; at night, h is typically below the top of the surface-based radiation inversion **[57]**.

The turbulent structure of the ABL is determined by the amount of heat released to the atmosphere from the earth's surface (sensible heat flux) and by interaction of the wind with the surface (momentum flux). This structure can be described using three length scales: z (the height above the surface), h (the mixing height), and L (the Obukhov length). The Obukhov length is defined by the surface fluxes of heat $H = \rho C_p \overline{w'\theta'}$ and momentum $u_*^2 = -\overline{u'w'}$, and reflects the height at which contributions to the turbulent kinetic energy from buoyancy and shear stress are comparable; the Obukhov length is defined as:

$$L = \frac{-u_*^3}{k\,(g/\theta)\,\overline{w'\theta'}} \qquad \textbf{(6.6.1)}$$

where k is the von Karman constant, θ is the mean potential temperature within the surface layer, g/θ is a buoyancy parameter, and u_* is the friction velocity. The three length scales define two independent non-dimensional parameters: a relative height scale (z/h), and a stability index (h/L)**[56]**.

Alternatives to the measurement of the surface fluxes of heat and momentum for use in (6.6.1) involve relating turbulence to the mean profiles of temperature and wind speed. The Richardson number, the ratio of thermal to mechanical production (destruction) of turbulent kinetic energy, is directly related to another non-dimensional stability parameter (z/L) and, thus, is a good candidate for an alternative to 6.6.1. The gradient Richardson number (R_g) can be approximated by:

$$R_g = \frac{g}{\overline{T}}\,\frac{\Delta\theta}{(\Delta u)^2}\,(z_2 - z_1) \qquad \textbf{(6.6.2)}$$

Large negative Richardson numbers indicate unstable conditions while large positive values indicate stable conditions. Values close to zero are indicative of neutral conditions. Use of (6.6.2) requires estimates of Δu based on measurements of wind speed at two levels in the surface layer; however, the level of accuracy required for these measurements is problematic (Δu is typically the same order of magnitude as the uncertainty in the wind speed measurement). The bulk Richardson number (R_b) which can be computed with only one level of wind speed is a more practical alternative:

$$R_b = \frac{g}{\overline{T}} \frac{\Delta\theta}{u^2} z \qquad \textbf{(6.6.3)}$$

6.6.1 The Profile Method

The bulk Richardson number given in (6.6.3) is perhaps the simplest and most direct approach for characterizing the surface layer. For example, given the necessary surface layer measurements, one can derive both H and u_* from the integrated flux-profile equations: **[51,52]**

$$\Delta u = \frac{u_*}{k} \left[\ln\left(\frac{z_{i+1}}{z_i}\right) - \psi_m\left(\frac{z_{i+1}}{L}\right) + \psi_m\left(\frac{z_i}{L}\right) \right] \qquad \textbf{(6.6.4)}$$

$$\Delta\theta = R \frac{\theta_*}{k} \left[\ln\left(\frac{z_{j+1}}{z_j}\right) - \psi_h\left(\frac{z_{j+1}}{L}\right) + \psi_h\left(\frac{z_j}{L}\right) \right] \qquad \textbf{(6.6.5)}$$

where $\Delta u = (u_{i+1} - u_i)$, $\Delta\theta = (\theta_{j+1} - \theta_j)$; R is a parameter associated with the emperically determined similarity functions, ψ_m and ψ_h . EPA recommends using the emperical functions given in reference **[59]**; in this case the von Karman constant, k = 0.4 and R = 1. The temperature scale θ_* is related to the heat flux by:

$$H = -\rho\, C_p\, u_*\, \theta_* \qquad \textbf{(6.6.6)}$$

Methods for solving the flux profile equations vary depending on what measurements are available. In the general case with two arbitrary levels each of temperature and wind speed [i.e., as in (6.6.4) and (6.6.5)], one can solve for the unknowns (u_*, θ_*, and L) by iteration; when temperature and wind speed are measured at the same heights, approximate analytic solutions can

be used. Other simplifications result by replacing the lower wind speed measurement height in (6.6.4), z_i, with the surface roughness length (z_0) **[51,52]** ; see Section 6.6.3 for guidance on estimating surface roughness. A least squares method **[49]** is recommended when wind speed and temperature data are available for three or more levels. To ensure the data are representative of the surface layer, the wind speed and tempreature sensors should be located between $20z_0$ and $100z_0$; for sites with very low roughness, the sensors should be located between 1 and 10 m. Sampling durations for use in computing 1-hour averages should be in the range of 3 to 60 minutes; a sampling duration of 15 minutes or less is recommended if the steady-state assumption is in doubt.

6.6.2 The Energy Budget Method

An equation expressing the partitioning of energy at the surface may be used in place of (6.6.5) when measurements of $\Delta\theta$ are not available**[53, 54, 58]**. The expression for the surface energy budget is:

$$H_0 + \lambda E = Q^* - G \qquad \textbf{(6.6.7)}$$

where λE is the latent heat flux (λ is the latent heat of water vaporization and E is the evaporation rate), Q* is the net radiation and G the soil heat flux. $H_0 + \lambda E$ is the energy flux that is supplied to or extracted from the air, while Q* - G is the source or sink for this energy. Using $H_0 = -\rho C_p u_* \theta_*$, (6.6.7) can be written as:

$$\theta_* = \frac{\lambda E - Q^* + G}{\rho C_p u_*} \qquad \textbf{(6.6.8)}$$

In this equation λE, Q* and G can be parameterized in terms of the total cloud cover N, the solar elevation ϕ, the air temperature T, the friction velocity u_* and θ_* itself. The idea is to use (6.6.8) to write θ_* as a function of the variables N, ϕ, T, and u_*:

$$\theta_* = f_2(N, \phi, T, u_*) \qquad \textbf{(6.6.9)}$$

This equation then replaces (6.6.5). The further procedure of finding θ_* and u_* from (6.6.4) and (6.6.9) by iteration is similar to that used in the profile method.

6.6.3 Surface Roughness Length

The roughness length (z_0) is related to the roughness characteristics of the terrain. Under near-neutral conditions and with a homogeneous distribution of obstacles, a local value of z_0 can be determined from the logarithmic wind profile.

$$U(z) = \frac{u_*}{k} \ln(z/z_0) \qquad \textbf{(6.6.10)}$$

For general application, since typical landscapes almost always contain occasional obstructions, one should attempt to estimate an effective roughness length. The recommended method for estimating the effective roughness length is based on single level gustiness measurements σ_u **[60]**:

$$\frac{\sigma_u}{\overline{u}} = \frac{1}{\ln(z/z_0)} \qquad \textbf{(6.6.11)}$$

Wind measurements for use in (6.6.11) should be made between 20 z_0 and 100 z_0; to select the appropriate measurement level, an initial estimate of the effective roughness length must first be made based on a visual inspection of the landscape (see roughness classifications provided in Table 6-10). The sampling duration for σ_u and $\overline{u}$ should be between 3 and 60 minutes. Data collected for use in estimating the effective surface roughness should be stratified by wind speed (only data for wind speeds greater than 5 m/s should be used) and wind direction sector (using a minimum sector arc width of 30 degrees). Median z_0 values should be computed for each sector; results should then be inspected to determine whether the variation between sectors is significant. An average of the median values should be computed for adjacent sectors if the variation is not significant. Estimates of the effective surface roughness using these procedures are accurate to one significant figure; i.e., a computed value of 0.34 m should be rounded to 0.3 m. Documentation of the successful application of these procedures is provided in reference **[61]**.

Table 6-10

Terrain Classification in Terms of Effective Surface Roughness Length, Z_0

Terrain Description	Z_0 (m)
Open sea, fetch at least 5 km	0.0002
Open flat terrain; grass, few isolated obstacles	0.03
Low crops, occasional large obstacles, x'/h > 20*	0.10
High crops, scattered obstacles, 15 < x'/h < 20*	0.25
Parkland, bushes, numerous obstacles, x'/h 10*	0.50
Regular large obstacle coverage (suburb, forest)	0.50 - 1.0

* x' = typical distance to upwind obstacle; h = height of obstacle

6.6.4 Guidance for Measurements in the Surface Layer

Monin-Obukhov (M-O) similarity theory is strictly applicable to steady-state horizontally homogeneous conditions in the surface layer. The temperature and wind speed measurements for use with M-O theory should be representative of a layer that is both high enough to be above the influence of the individual surface roughness elements and yet low enough to be within the surface layer; as a rule of thumb, the measurements should be made within the layer from $20z_0$ to $100z_0$ above the surface (2 - 10 m for a surface roughness of 0.1 m) **[57]**.

Data quality objectives and, consequently, instrument specifications for monitoring of temperature and wind speed in the surface layer are determined by the limitations imposed during the extreme stability conditions; basically this requires a monitoring design with the capability to resolve the variable gradients in temperature and wind speed that can exist within the surface layer under various conditions.

The depth of the surface layer where M-O similarity theory applies ranges from about one tenth of the ABL depth (h) during neutral conditions (typically 500 - 600 m) to the lesser of $|L|$ or 0.1 h during non-neutral conditions (less than 10 m during extreme stability conditions). This variability in the depth of the surface layer imposes limitations on what can be accomplished with a single fixed set of sensors. To ensure the availability of measurements representative of the entire surface layer during all stability conditions, one should employ a tall-tower (60 m or taller) equipped with wind and temperature sensors at several levels including, as a minimum, 2, 10 and 60 m. In the absence of a tall-tower, a standard 10-meter meteorological tower equipped with a single fixed set of sensors should be employed. Wind speed should be measured at the standard height of 10 m; the temperature difference should be measured between 2 and 10 m (for $z_0 \sim 0.1$ m). The usefulness of such a relatively low-lying measurement configuration lies in its applicability to both stable and unstable atmospheric conditions.

Application of M-O similarity should generally be restricted to low roughness sites located in relatively homogeneous terrain. For such sites, the reliability of the profile method for estimating surface layer parameters is primarily dependent on accurate temperature difference measurements (see Section 3.2.2 for siting and exposure of temperature sensors and Section 5.1 for sensor specifications).

6.7 Use of Airport Data

Airport data refers to surface weather observations collected in support of various NWS and Federal Aviation Administration (FAA) programs; most, although not all, of the surface weather observation sites are located at airports. For practical purposes, because airport data are readily available, most regulatory modeling was initially performed using these data. However, airport data do not meet this guidance - significant deviations include:

- The instruments used at airports are generally more robust and less sensitive than the instruments recommended in this guidance. For example, the thresholds for measuring wind direction and wind speed are higher than is recommended in this guidance; this results in a greater incidence of calms in airport data.
- Wind direction in airport data bases is reported to the nearest ten degrees - one degree resolution of wind direction is recommended in this guidance.
- Airport data for wind direction and wind speed are 2-minute averages; data for other variables, e.g., temperature and pressure are instantaneous readings - hourly averaging is recommended for all variables in this guidance.

Although data meeting this guidance are preferred, airport data continue to be acceptable for use in modeling. In fact observations of cloud cover and ceiling, data which traditionally have been provided by manual observation, are only available routinely in airport data; both of these variables are needed to calculate stability class using Turner's method (Section 6.4.1). The Guideline on Air Quality Models **[1]** recommends that modeling applications employing airport data be based on consecutive years of data from the most recent, readily available 5-year period. Airport data are available on the National Climatic Data Center (NCDC) World Wide Web site at http://www.ncdc.noaa.gov/. Documentation and guidance on NWS surface weather observations is provided in the Federal Meteorological Handbook No. 1 "Surface Weather Observations and Reports" **[62]**.

6.8 Treatment of Missing Data

Missing or invalid data should be flagged or replaced as appropriate depending on the model to be used. Note that the ISCST3 model recognizes specific flags for missing data; however, many models do not recognize flags and will not accept missing or invalid data. For use in these models, data bases with isolated one-hour gaps should be filled with estimates based on persistence or linear interpolation. Application specific procedures should be used for filling longer gaps; guidance for developing such procedures is provided in Section 6.8.1. Substitutions for missing data should only be made to complete the data set for modeling applications; substitution should not be used to attain the 90% completeness requirement for regulatory modeling applications (Section 5.3.2).

6.8.1 Substitution Procedures

This section provides general guidance on substitution procedures for use in completing meteorological data bases prior to their use in modeling. It is intended for use by applicants and reviewing agencies in the development of substitution protocols for application to regulatory air quality dispersion modeling. Substitution protocols should be included in a modeling protocol and submitted for approval to the reviewing authority prior to the modeling analysis.

Substitution procedures will vary depending on the nature of the application, the availability of alternative sources of meteorological data, and the extent of the missing or invalid data. If the data base is such that there are relatively few isolated one-hour gaps, then an interpolation procedure, which is easily automated, may provide the most practical method of substitution. However, it there are lengthy periods with missing or invalid data, then application specific procedures will generally be necessary.

The goal of substitution should be to replace missing data with a "best estimate" so as to minimize the probable error of the estimate. The following suggestions have been prioritized in order of increasing probable error.

Substitution procedures which are considered to be "best estimators" include the following:

- Persistence - Persistence is the use of data from the previous time period (hour). This procedure is applicable for most meteorological variables for isolated one-hour gaps; caution should be used when the gaps occur during day/night transition periods.
- Interpolation - This procedure is applicable for most meteorological variables for isolated one-hour gaps and, depending on circumstances, may be used for more extended periods (several hours) for selected variables; e.g., temperature. As in the case of persistence, caution should be used when the gaps occur during day/night transition periods.
- Profiling - Profiling (profile extrapolation) refers to the procedure in which missing data for one level in a multi-level data base (e.g., data from a meteorological tower) is replaced by an estimate based on data from an alternative level or levels in the same data base. The probable error of the profiling estimate does not increase with the duration of the missing data, as is the case for persistence and interpolation. Consequently, profiling becomes a better estimator compared to persistence and interpolation as the length of the missing data period increases. Profiling based on a power-law should be used for extrapolating wind speed with height; the stability dependent procedure discussed in Section 6.2.5 is recommended. Profiling based on lapse rate should be used for extrapolating temperature with height. Alternatively, with the approval of the reviewing authority, applicants may use site-specific profiling procedures for wind speed and temperature.

Substitution procedures which provide estimators with moderate probable error include the following:

- Substitution from sensors located at comparable levels at nearby locations with similar site-specific (surface-specific) characteristics.
- Persistence when used for more than several hours.
- Interpolation when used for more than several hours.

Substitution procedures which provide estimators with high probable error include the following:

- Substitution from measurements at nearby locations with dissimilar site-specific (surface-specific) characteristics.
- Substitution of a climatological value for a particular time period; e.g., a seasonal or monthly average.
- Substitution of simulated meteorology based, for example, on a boundary layer model.
- Substitution of "dummy data" such as a constant value for a variable.

6.9 Recommendations

The hourly scalar mean wind speed and wind direction should be used in steady-state Gaussian dispersion models. These statistics should be processed using the methods provided in Section 6.2.1; unit vector processing (Section 6.2.2) may also be used to estimate the hourly scalar mean wind direction. The standard deviation of the wind direction should be calculated using the techniques described in Section 6.2.1. Hourly statistics may be obtained by processing samples over an entire hour or by averaging sub-hourly statistics. The recommended sub-hourly averaging interval for wind data processing is 15 minutes; two valid 15-minute averages are required for a valid hourly average.

For the purposes of this guidance, a calm occurs when the wind speed is below the starting threshold of the anemometer or vane, whichever is greater. Calms require special treatment in such applications to avoid division by zero in the steady-state dispersion algorithm. For similar reasons, to avoid unrealistically high concentration estimates at low wind speeds (below the values used in validations of these models - about 1 m/s) EPA recommends that wind speeds less than 1 m/s be reset to 1 m/s for use in steady-state dispersion models; the unaltered data should be retained for use in non-steady-state modeling applications. Calms should be identified in processed data files by flagging the appropriate records; user's guides for the model being used should be consulted for model specific flagging conventions.

Recommended sampling and processing strategies for the primary meteorological variables for various applications are given in Table 6-1.

The Pasquill-Gifford (P-G) stability category should be determined with Turner's method (Section 6.4.1) using site-specific wind speed measurements at or near 10 m and representative

cloud cover and ceiling height. Other approved methods for estimating the P-G stability category, for use when representative cloud cover and ceiling observations are not available, include the solar radiation delta-T (SRDT) method described in Section 6.4.2, and turbulence-based methods using site-specific wind fluctuation statistics: σ_E (Section 6.4.3) or σ_A (Section 6.4.4). Alternative methods for determining stability category should be evaluated in consultation with the Regional Office.

Emperical relationships for use in models employing boundary layer scaling techniques should be selected in accordance with a von Karmam constant of 0.4; recmmended emperical relationships are given in reference ***[59]****.*

Missing data should be flagged or replaced as appropriate depending on the model to be used. Isolated one-hour gaps in meteorological data bases used in regulatory modeling should be filled with estimates bases on persistence or interpolation. Application specific procedures should be used to fill longer gaps

If the recommendations in this section cannot be achieved, then alternative approaches should be developed in consultation with the EPA Regional Office.

7. DATA REPORTING AND ARCHIVING

Meteorological data collected for use in regulatory modeling applications should be made available to the regulatory agency as necessary. In some cases, as part of an oversight function, agencies may require periodic or even real-time access to the data as it is being collected. The regulatory agency may, in addition, require long-term archival of meteorological data bases used in some applications [e.g., analyses supporting State Implementation Plan (SIP) actions and Prevention of Significant deterioration (PSD) permits]. Procedures for compliance with such requirements should be worked out with the agency and documented in the monitoring protocol prior to commencement of monitoring.

7.1 Data Reports

The following general recommendations apply to meteorological data bases being prepared for use in regulatory modeling applications. All meteorological data should be reduced to hourly averages using the procedures provided in Section 6. The data should be recorded in chronological order; records should be labeled according to the observation time (defined as the time at the end of the averaging period; i.e., the hour ending). If possible, each data record should contain the data for one hourly observation (one record per hour). The first four fields of each data record should identify the year, month, day and hour of the observation. The data records should be preceded by a header record providing the following information:

- Station name
- Station location (latitude, longitude, and time zone)
- Station elevation
- Period of record and number of records
- Validation level (see Section 8)

A summary report should accompany each meteorological data base prepared for use in regulatory modeling applications. The summary report should provide the following information:

- number and percent of hours with complete/valid data.
- number and percent of hours with valid stability data.
- number and percent of hours with valid wind speed and wind direction data including valid calms.
- list of hours requiring substitutions including identification of the missing variable and the substitution protocol employed.

7.2 Data Archives

Meteorological data used in support of some regulatory actions (e.g, SIP revisions and PSD permit applications) may be needed in support of continuing actions for these regulations and, consequently should be archived by the agency with permit granting authority; normally the State. Such an archive should be designed for the data actually used in the regulatory application - i.e., the processed data, but may also include some raw data. Archival of other raw data is at the discretion of the applicant. The processed meteorological data should be archived initially for one year with provisions for review and extension to five years, ten years, or indefinite. Where data were originally reduced from strip chart records, the charts should also be archived. Original strip chart records should be retained for a minimum of five years. If an archive is to be eliminated, an attempt should be made to contact potential user's who might be affected by such an action.

7.3 Recommendations

Procedures for compliance with reporting and archiving requirements should be worked out with the agency and documented in the monitoring protocol prior to commencement of monitoring.

Meteorological data provided to regulatory agencies for use in modeling should be reduced to hourly averages using the procedures provided in Section 6. The data should be recorded in chronological order; records should be labeled according to the observation time (defined as the time at the end of the averaging period; i.e., the hour ending).

Meteorological data used in support of SIP revisions or PSD permit applications should be archived initially for one year with provisions for review and extension to five years, ten years, or indefinite.

8. QUALITY ASSURANCE AND QUALITY CONTROL

Quality Assurance/Quality Control (QAQC) procedures are required to ensure that the data collected meet standards of reliability and accuracy (see Section 5.1). Quality Control (QC) is defined as those operational procedures that will be routinely followed during the normal operation of the monitoring system to ensure that a measurement process is working properly. These procedures include periodic calibration of the instruments, site inspections, data screening, data validation, and preventive maintenance. The QC procedures should produce quantitative documentation to support claims of accuracy. Quality Assurance (QA) is defined as those procedures that will be performed on a more occasional basis to provide assurance that the measurement process is producing data that meets the data quality objectives (DQO). These procedures include routine evaluation of how the QC procedures are implemented (system audits) and assessments of instrument performance (performance audits).

The QAQC procedures should be documented in a Quality Assurance Project Plan (QAPP) and should include a "sign-off" by the appropriate project or organizational authority. The QAPP should include the following **[63]**:

1. Project description - how meteorology is to be used
2. Project organization - how data validity is supported
3. QA objective - how QA will document validity claims
4. Calibration method and frequency - for meteorology
5. Data flow - from samples to archived valid values
6. Validation and reporting methods - for meteorology
7. Audits - performance and system
8. Preventive maintenance
9. Procedures to implement QA objectives - details
10. Management support - corrective action and reports

It is important that the person providing the QA be independent of the organization responsible for the collection of the data and the maintenance of the measurement systems. Ideally, this person should be employed by an independent company. There should not be any lines of intimidation available to the operators which might be used to influence the QA audit report and actions. With identical goals of valid data, the QA person should encourage the operator to use the same methods the QA person uses (presumably these are the most comprehensive methods) when challenging the measurement system during a performance audit. When this is done, the QA task reduces to spot checks of performance and examination of records thus providing the best data with the best documentation at the least cost.

8.1 Instrument Procurement

The specifications required for the applications for which the data will be used (see Sections 5.0 and 6.0) along with the test method to be used to determine conformance with the specification should be a part of the procurement document. A good QA Plan will require a QA sign-off of the procurement document for an instrument system containing critical requirements. An instrument should not be selected solely on the basis of price and a vague description, without detailed documentation of sensor performance.

8.1.1 Wind Speed

This section provides guidance for procurement of anemometers (i.e., mechanical wind speed sensors employing cups or vane-oriented propellers) which rely on the force of the wind to turn a shaft. Guidance for the procurement of remote sensors for the measurement of wind speed is provided in Section 9. Other types of wind speed sensors (e.g., hot wire anemometers and sonic anemometers) are not commonly used for routine monitoring and are beyond the scope of this guide. An example performance specification for an anemometer is shown in Table 8-1.

Table 8-1

Example Performance Specification for an Anemometer

Range	0.5 m/s to 50 m/s
Threshold[1]	$\leq$ 0.5 m/s
Accuracy (error)[1,2]	$\leq$ (0.2 m/s + 5% of observed)
Distance Constant[1]	$\leq$ 5 m at 1.2 kg/m^3 (at std sea-level density)

[1] As determined by wind tunnel test conducted on production samples in accordance with ASTM D-22.11 test methods

[2] aerodynamic shape (cup or propeller) with permanent serial number to be accompanied by test report, traceable to NBS, showing rate of rotation vs. wind speed at 10 speeds.

The procurement document should ask for (1) the starting torque of the anemometer shaft (with cup or propeller removed) which represents a new bearing condition, and (2) the starting torque above which the anemometer will be out of specification.; when the latter value is exceeded, the bearings should be replaced.

The ASTM test cited above includes a measurement of off-axis response. Some anemometer designs exhibit errors greater than the accuracy specification with off-axis angles of as little as 10 degrees. However, there is no performance specification for this type of error at this time, due to a lack of sufficient data to define what the specification should be.

8.1.2 Wind Direction

This section provides guidance for procurement of wind vanes; i.e., mechanical wind direction sensors which rely on the force of the wind to turn a shaft. Guidance for the procurement of remote sensors for the measurement of wind direction is provided in Section 9.

The wind direction measurement with a wind vane is a relative measurement with respect to the orientation of the direction sensor. There are three parts to this measurement which must be considered in quality assurance. These are: (l) the relative accuracy of the vane performance in converting position to output, (2) the orientation of the vane both horizontal (with respect to "true north") and vertical (with respect to a level plane), and (3) the dynamic response of the vane and conditioning circuit to changes in wind direction.

The procurement document should ask for: (1) the starting torque of the vane shaft (with the vane removed) which represents a new bearing (and potentiometer) condition, and (2) the starting torque above which the vane will be out of specification.; when the latter value is exceeded, the bearings should be replaced. An example performance specification for a wind vane is shown in Table 8-2.

Table 8-2

Example Performance Specification for a Wind Vane

Range	1 to 360 or 540 degrees
Threshold[1]	$\leq$ 0.5 m/s
Accuracy (error)[1]	$\leq$ 3 degrees relative to sensor mount or index
	$\leq$ 5 degrees absolute error for installed system
Delay Distance[1]	$\leq$ 5 m at 1.2 kg/m^3 (at std sea-level density)
Damping Ratio[1]	$\geq$ 0.4 at 1.2 kg/m^3 or
Overshoot[1]	$\leq$ 25% at 1.2 kg/m^3

[1] As determined by wind tunnel test conducted on production samples in accordance with ASTM D-22.11 test methods

The range of 1 to 540 degrees was originally conceived to minimize strip chart "painting" when the direction varied around 360 degrees. It also minimizes errors (but does not eliminate them) when sigma meters are used. It may also provide a means of avoiding some of the "dead band" errors from a single potentiometer. In these days of "smart" data loggers, it is possible to use a single potentiometer (1 to 360 degree) system without excessive errors for either average direction or σ_A.

If the wind direction samples are to be used for the calculation of σ_A, the specification should also include a time constant requirement for the signal conditioner. Direction samples should be effectively instantaneous. At 5 m/s, a 1m delay distance represents 0.2 seconds. A signal conditioner specification of a time constant of <0.2 seconds would insure that the σ_A value was not attenuated by an averaging circuit provided for another purpose.

8.1.3 Temperature and Temperature Difference

When both temperature and differential temperature are required, it is important to specify both accuracy and relative accuracy (not to be confused with precision or resolution). Accuracy is performance compared to truth, usually provided by some standard instrument in a controlled environment. Relative accuracy is the performance of two or more sensors, with respect to one of the sensors or the average of all sensors, in various controlled environments. A temperature sensor specification might read:

Range	-40 to +60 °C.
Accuracy (error)	$\leq$ 0.5 °C.

A temperature difference specification might read:

Range	-5 to +15 °C.
Relative accuracy (error)	$\leq$ 0.1 °C.

While calibrations and audits of both accuracy and relative accuracy are usually conducted in controlled environments, the measurement is made in the atmosphere. The greatest source of error is usually solar radiation. Solar radiation shield specification is therefore an important part of the system specification. Motor aspirated radiation shields (and possibly high performance naturally ventilated shields) will satisfy the less critical temperature measurement. For temperature difference, it is critical that the same design motor aspirated shield be used for both sensors. The expectation is that the errors from radiation (likely to exceed 0.2 °C) will zero out in the differential measurement. A motor aspirated radiation shield specification might read:

Radiation range	-100 to 1300 W/m^2
Flow rate	3 m/s or greater
Radiation error	< 0.2 °C.

8.1.4 Dew Point Temperature

Sensors for measuring dew point temperature can be particularly susceptible to precipitation, wind, and radiation effects. Therefore, care should be taken in obtaining proper (manufacturer-recommended) shielding and aspiration equipment for the sensors. If both temperature and dew point are to be measured, aspirators can be purchased which will house both sensors. If measurements will be taken in polluted atmospheres, gold wire electrodes will minimize corrosion problems. For cooled mirror sensors consideration should be given to the susceptibility of the mirror surface to contamination.

8.1.5 Precipitation

For areas where precipitation falls in a frozen form, consideration should be given to ordering an electrically heated rain and snow gauge. AC power must be available to the precipitation measurement site. For remote sites where AC power is not available, propane-heated gauges can be ordered. However, if air quality measurements are being made at the same location, consideration should be given to the air pollutant emissions in the propane burner exhaust.

Air movement across the top of a gauge can affect the amount of catch. For example, Weiss **[64]** reports that at a wind speed of 5 mph, the collection efficiency of an unshielded gauge decreased by 25%, and at 10 mph, the efficiency of the gauge decreased by 40%. Therefore, it is recommended that all precipitation gauges be installed with an Alter-type wind screen, except in locations where frozen precipitation does not occur.

Exposure is very important for precipitation gauges; the distance to nearby structures should be at least two to four times the height of the structures (see Section 3.1.3). Adequate lengths of cabling must be ordered to span the separation distance of the gauge from the data acquisition system. If a weighing gauge will be employed, a set of calibration weights should be obtained.

8.1.6 Pressure

The barometric pressure sensor should normally have a proportional and linear electrical output signal for data recording. Alternately, a microbarograph can be used with a mechanical recording system. Some barometers operate only within certain pressure ranges; for these, care should be taken that the pressure range is appropriate for the elevation of the site where measurements will be taken.

8.1.7 Radiation

Radiation instruments should be selected from commercially available and field-proven systems. These sensors generally have a low output signal, so that they should be carefully matched with the signal conditioner and data acquisition system. Another consideration in the

selection of data recording equipment is the fact that net radiometers have both positive and negative voltage output signals.

8.2 Installation and Acceptance Testing

The installation period is the optimal time to receive appropriate training in instrument principles, operations, maintenance, and troubleshooting, as well as data interpretation and validation. Meteorological consultants as well as some manufacturers and vendors of meteorological instruments provide these services.

An acceptance test is used to determine if an instrument performs according to the manufacturer's specifications **[2]**. Manufacturer's procedures for unpacking, inspection, installation, and system diagnostics should be followed to assure that all components are functioning appropriately. All acceptance-testing activities should be documented in the station log.

8.2.1 Wind Speed

This section provides guidance for the acceptance testing of anemometers (i.e., mechanical wind speed sensors employing cups or vane-oriented propellers) which rely on the force of the wind to turn a shaft. Guidance for the acceptance testing of remote sensors for the measurement of wind speed is provided in Section 9. Other types of wind speed sensors (e.g., hot wire anemometers and sonic anemometers) are not commonly used for routine monitoring and are beyond the scope of this guide.

A technical acceptance test may serve two purposes. First, it can verify that the instrument performs as the manufacturer claims, assuming the threshold, distance constant and transfer function (rate of rotation vs. wind speed) are correct. This test catches shipping damage, incorrect circuit adjustments, poor workmanship, or poor QA by the manufacturer. This level of testing should be equivalent to a field performance audit. The measurement system is challenged with various rates of rotation on the anemometer shaft to test the performance from the transducer in the sensor to the output. The starting torque of the bearing assembly is measured and compared to the range of values provided by the manufacturer (new and replacement).

The other purpose of a technical acceptance test is to determine if the manufacturer really has an instrument which will meet the specification. This action requires a wind tunnel test. The results would be used to reject the instrument if the tests showed failure to comply. An independent test laboratory is recommended for conducting the ASTM method test.

The specification most likely to fail for a low cost anemometer is threshold, if bushings are used rather than quality bearings. A bushing design may degrade in time faster than a well designed bearing assembly and the consequence of a failed bushing may be the replacement of the whole anemometer rather than replacement of a bearing for a higher quality sensor. A receiving inspection cannot protect against this problem. A mean-time-between-failure

specification tied to a starting threshold torque test is the only reasonable way to assure quality instruments if quality brand names and model numbers cannot be required.

8.2.2 Wind Direction

This section provides guidance for the acceptance testing of wind vanes; i.e., mechanical wind direction sensors which rely on the force of the wind to turn a shaft. Guidance for the acceptance testing of remote sensors for the measurement of wind direction is provided in Section 9.

A technical acceptance test can verify the relative direction accuracy of the wind vane by employing either simple fixtures or targets within a room established by sighting along a 30-60-90 triangle. There is no acceptance test for sighting or orientation, unless the manufacturer supplies an orientation fixture and claims that the sensor is set at the factory to a particular angle (180 degrees for example) with respect to the fixture.

If σ_A is to be calculated from direction output samples, the time constant of the output to an instantaneous change should be estimated. If the direction output does not change as fast as a test meter on the output can react, the time constant is too long.

If σ_A is calculated by the system, a receiving test should be devised to check its performance. The manual for the system should describe tests suitable for this challenge.

8.2.3 Temperature and Temperature Difference

The simplest acceptance test for temperature and temperature difference would be a two point test, room temperature and a stirred ice slurry. A reasonably good mercury-in-glass thermometer with some calibration pedigree can be used to verify agreement to within l °C. It is important to stir the liquid to avoid local gradients. It should not be assumed that a temperature difference pair will read zero when being aspirated in a room. If care is taken that the air drawn into each of the shields comes from the same well mixed source, a zero reading might be expected.

A second benefit of removing the transducers from the shields for an acceptance test comes to the field calibrator and auditor. Some designs are hard to remove and have short leads. These conditions can be either corrected or noted when the attempt is first made in the less hostile environment of a receiving space.

8.2.4 Dew Point Temperature

A dew point temperature acceptance test at one point inside a building, where the rest of the system is being tested, will provide assurance that connections are correct and that the operating circuits are functioning. The dew point temperature for this test should be measured with a wet-dry psychrometer (Assman type if possible) or some other device in which some measure of accuracy is documented. If it is convenient to get a second point outside the building,

assuming that the dew point temperature is different outside (usually true if the building is air conditioned with water removed or added), further confidence in the performance is possible. Of course, the manufacturer's methods for checking parts of the system (see the manual) should also be exercised.

8.2.5 Precipitation

The receiving inspection for a precipitation gauge is straightforward. With the sensor connected to the system, check its response to water (or equivalent weight for weighing gauges) being introduced into the collector. For tipping bucket types, be sure that the rate is less than the equivalent of one inch (25mm) per hour if the accuracy check is being recorded. See the section on calibration (8.3) for further guidance.

8.2.6 Pressure

A check inside the building is adequate for an acceptance test of atmospheric pressure. An aneroid barometer which has been set to agree with the National Weather Service (NWS) equivalent sea-level pressure can be used for comparison. If station pressure is to be recorded by the pressure sensor, be sure that the aneroid is set to agree with the NWS station pressure and not the pressure broadcast on radio or television. A trip to the NWS office may be necessary to set the aneroid for this agreement since the station pressure is sensitive to elevation and the NWS office may be at a different elevation than the receiving location.

8.2.7 Radiation

A simple functional test of a pyranometer or solarimeter can be conducted with an electrical light bulb. With the sensor connected to the system as it will be in the field, cover it completely with a box with all cracks taped with an opaque tape. Any light can bias a "zero" check. The output should be zero. Do not make any adjustments without being absolutely sure the box shields the sensor from any direct, reflected, or diffuse light. Once the zero is recorded, remove the box and bring a bulb (100 watt or similar) near the sensor. Note the output change. This only proves that the wires are connected properly and the sensor is sensitive to light.

If a net radiometer is being checked, the bulb on the bottom should induce a negative output and on the top a positive output. A "zero" for a net radiometer is much harder to simulate. The sensor will (or may) detect correctly a colder temperature on the bottom of the shielding box than the top, which may be heated by the light fixtures in the room. Check the manufacturer's manual for guidance.

8.3 Routine Calibrations

A calibration involves measuring the conformance to or discrepancy from a specification for an instrument and an adjustment of the instrument to conform to the specification.

Documentation of all calibrations should include a description of the system "as found", details of any adjustments to the instrument, and a description of the system "as left"; this documentation is a vital part of the "paper-trail" for any claims of data validity. Calibrations are often confused with performance audits since both involve measuring the conformance of an instrument to a specification; the main difference has to do with the independence of the person performing the audit or calibration - the performance audit should be conducted by a person who is independent of the operating organization - calibrations, on the other hand, are often performed by individuals within the operating organization. Guidance specific to performance audits is provided in Section 8.4.

The guidance provided on calibration procedures in the following applies to in situ meteorological sensors such as would be mounted on a tower (e.g., wind vanes and anemometers) or located at ground level (e.g., a solar radiation sensor). Ideally, a calibration should be performed in an environment as close as possible to laboratory bench-test as conditions allow. For tower mounted sensors this usually involves removing the sensor from tower. The alternative to a bench-test calibration of the in situ sensor is a calibration using a collocated transfer standard; this involves locating an identical standard instrument as close as practical to the instrument being calibrated. The collocated standard transfer method is the most complete calibration/audit method from the standpoint of assessing total system error. However it has two serious drawbacks: 1) it is limited to the conditions that prevailed during the calibration/audit, and 2) it is sensitive to siting and exposure bias.

Calibrations using a bench test or collocated transfer standard are not generally applicable to the upper-air measurement systems; the special procedures required for calibrations and audits of upper-air measurement systems are discussed in Section 9.

Documentation supplied with newly purchased instruments should include the manufacturer's recommended calibration procedures. The guidance on calibration procedures provided in the following is intended to supplement the manufacturer's recommendations; when in doubt, the instrument manufacturer should be consulted.

8.3.1 Sensor Check

There are three types of action which can be considered a sensor check. First, one can look at and perform "housekeeping" services for the sensors. Secondly, one can measure some attribute of the sensor to detect deterioration in anticipation of preventative maintenance. Thirdly, the sensor can be subjected to a known condition whose consequence is predictable through the entire measurement system, including the sensor transducer. Each of these will be addressed for each variable, where appropriate, within the divisions of physical inspection and measurement and accuracy check with known input.

8.3.1.1 Physical inspection

The first level of inspection is visual. The anemometer and vane can be looked at, either directly or through binoculars or a telescope, to check for physical damage or signs of erratic

behavior. Temperature shields can be checked for cleanliness. Precipitation gauges can be inspected for foreign matter which might effect performance. The static port for the atmospheric pressure system also can be examined for foreign matter. Solar radiation sensors should be wiped clean at every opportunity.

A better level of physical inspection is a "hands on" check. An experienced technician can feel the condition of the anemometer bearing assembly and know whether or not they are in good condition. This is best done with the aerodynamic shape (cup wheel, propeller, or vane) removed. Caution: Damage to anemometers and vanes is more likely to result from human handling than from the forces of the wind, especially during removal or installation and transport up and down a tower. The proper level of aspiration through a forced aspiration shield can be felt and heard under calm condition.

The best level of sensor check is a measurement. The anemometer and wind vane sensors have bearings which will certainly degrade in time. The goal is to change the bearings or the sensors before the instrument falls below operating specifications. Measurements of starting torque will provide the objective data upon which maintenance decisions can be made and defended. The presence, in routine calibration reports, of starting torque measurements will support the claim for valid data, if the values are less than the replacement torques.

The anemometer, identified by the serial number of the aerodynamic shape, should have a wind tunnel calibration report (see Section 8.1) in a permanent record folder. This is the authority for the transfer function (rate of rotation to wind speed) to be used in the next section. The temperature transducers, identified by serial number, should have calibration reports showing their conformity for at least three points to their generic transfer function (resistance to temperature, usually). These reports should specify the instruments used for the calibration and the method by which the instruments are tied to national standards (NBS). The less important sensors for solar radiation and atmospheric pressure can be qualified during an audit for accuracy.

8.3.1.2 Accuracy check with known input

Two simple tests will determine the condition of the anemometer (assuming no damage is found by the physical inspection). The aerodynamic shape must be removed. The shaft is driven at three known rates of rotation. The rates are known by independently counting shaft revolutions over a measured period of time in synchronization with the measurement system timing. The rates should be meaningful such as the equivalent of 2 m/s, 5 m/s and 10 m/s. Conversion of rates of rotation to wind speed is done with the manufacturer's transfer function or wind tunnel data. For example, if the transfer function is m/s = 1.412 r/s + 0.223, then rates of rotation of 1.3, 3.4 and 6.9 revolutions per second (r/s) would be equivalent to about 2, 5 and 10 m/s. All that is being tested is the implementation of the transfer function by the measuring system. The output should agree within one increment of resolution (probably 0.1 m/s). If problems are found, they might be in the transducer, although failures there are usually catastrophic. The likely source of trouble is the measurement system (signal conditioner, transmitting system, averaging system and recording system).

The second test is for starting torque. This test requires a torque watch or similar device capable of measuring in the range of 0.1 to 10 gm-cm depending upon the specifications provided by the manufacturer.

A successful response to these two tests will document the fact that the anemometer is operating as well as it did at receiving inspection, having verified threshold and accuracy. Changes in distance constant are not likely unless the anemometer design has changed. If a plastic cup is replaced by a stainless steel cup, for example, both the transfer function and the distance constant will likely be different. The distance constant will vary as the inverse of the air density. If a sea-level distance constant is 3.0 m, it may increase to 3.5 m in Denver and 4.3 m at the mountain passes in the Rockies.

For wind direction, a fixture holding the vane, or vane substitute, in positions with a known angle change is a fundamental challenge to the relative accuracy of the wind vane. With this method, applying the appropriate strategy for 360 or 540 degree systems, the accuracy of the sensor can be documented. The accuracy of the wind direction measurement, however, also depends on the orientation of the sensor with respect to true north.

The bearing to distant objects may be determined by several methods. The recommended method employs a solar observation (see Reference 3, p.11) to find the true north-south line where it passes through the sensor mounting location. Simple azimuth sighting devices can be used to find the bearing of some distant object with respect to the north-south line. The "as found" and "as left" orientation readings should report the direction to or from that distant object. The object should be one toward which the vane can be easily aimed and not likely to become hidden by vegetation or construction.

There are two parts of most direction vanes which wear out. One part is the bearing assembly and the other is the transducer, usually a potentiometer. Both contribute to the starting torque and hence the threshold of the sensor. A starting torque measurement will document the degradation of the threshold and flag the need for preventive maintenance. An analog voltmeter or oscilloscope is required to see the noise level of a potentiometer. Transducer noise may not be a serious problem with average values but it is likely to have a profound effect on σ_A.

The dynamic performance characteristics of a wind vane are best measured with a wind tunnel test. A generic test of a design sample is adequate. As with the anemometer, the dynamic response characteristics (threshold, delay distance and damping ratio) are density dependent.

Temperature transducers are reasonably stable, but they may drift with time. The known input for a temperature transducer is a stable thermal mass whose temperature is known by a standard transducer. The ideal thermal mass is one with a time constant on the order of an hour in which there are no thermal sources or sinks to establish local gradients within the mass. It is far more important to know what a mass temperature is than to be able to set a mass to a particular temperature.

For temperature difference systems, the immersion of all transducers in a single mass as described above will provide a zero-difference challenge accurate to about 0.01 °C. When this test is repeated with the mass at two more temperatures, the transducers will have been challenged with respect to how well they are matched and how well they follow the generic

transfer function. Mass temperatures in the ranges of 0 to 10 °C, 15 to 25 °C, and 30 to 40 °C are recommended. A maximum difference among the three temperatures (i.e., 0, 20, and 40 °C) is optimum. Once the match has been verified, known resistances can be substituted for the transducers representing temperatures, according to the generic transfer function, selected to produce known temperature difference signals to the signal conditioning circuitry. This known input will challenge the circuitry for the differential measurement.

Precipitation sensors can be challenged by inserting a measured amount of water, at various reasonable rainfall rates such as 25 mm or less per hour. The area of the collector can be measured to calculate the amount of equivalent rainfall which was inserted. The total challenge should be sufficient to verify a 10% accuracy in measurement of water. This does not provide information about errors from siting problems or wind effects.

Dew point temperature (or relative humidity), atmospheric pressure and radiation are most simply challenged in an ambient condition with a collocated transfer standard. An Assmann psychrometer may be used for dew point. An aneroid barometer checked against a local National Weather Service instrument is recommended for atmospheric pressure. Another radiation sensor with some pedigree or manufacturer's certification may be used for pyranometers and net radiometers. A complete opaque cover will provide a zero check.

8.3.2 Signal Conditioner and Recorder Check

For routine calibration of measurement circuits and recorders, use the manufacturer's recommendations. The outputs required by the test described in 8.3.1.2 must be reflected in the recorded values. Wind speed is used as an example in this section. Other variables will have different units and different sensitivities but the principle is the same. For sub-system checks, use the manual for specific guidance.

8.3.2.1 Analog system

Some systems contain "calibration" switches which are designed to test the stability of the circuits and to provide a basis for adjustment if changes occur. These should certainly be exercised during routine calibrations when data loss is expected because of calibration. In the hierarchy of calibrations, wind tunnel is first, known rate of rotation is second, substitute frequency is third and substitute voltage is fourth. The "calibration" switch is either third or fourth.

If analog strip chart recorders are used, they should be treated as separate but vital parts of the measurement system. They simply convert voltage or current to a mark on a time scale printed on a continuous strip of paper or composite material. The output voltage or current of the signal conditioner must be measured with a calibrated meter during the rate of rotation challenge. A simple transfer function, such as 10 m/s per volt, will provide verification of the measurement circuit at the output voltage position. The recorder can be challenged separately by inputting known voltages and reading the mark on the scale, or by noting the mark position when the rate

of rotation and output voltage are both known. See the recorder manual for recommendations should problems arise.

This special concern with recorders results from the variety of problems which analog recorders can introduce. A good measurement system can be degraded by an inappropriate recorder selection. If resolution is inadequate to distinguish between 1.3 m/s and 1.5 m/s, a 0.2 m/s accuracy is impossible. If enough resolution is just barely there, changes in paper as a function of relative humidity and changes in paper position as it passes the marking pen and excessive pen weight on the paper can be the limit of accuracy in the measurement. If the strip chart recorder is used only as a monitor and not as a backup for the primary system, its accuracy is of much less importance. The recorder from which data are recovered for archiving is the only recorder subject to measurement accuracy specifications.

8.3.2.2 Digital system

A digital system may also present a variety of concerns to the calibration method. One extreme is the digital system which counts revolutions or pulses directly from the sensor. No signal conditioning is used. All that happens is controlled by the software of the digital system and the capability of its input hardware to detect sensor pulses and only sensor pulses. The same challenge as described in 8.3.1.2 is used. The transfer function used to change rate of rotation to m/s should be found in the digital software and found to be the same as specified by the manufacturer or wind tunnel test. If any difference is found between the speed calculated from the known number of revolutions in the synchronous time period and the speed recorded in the digital recorder, a pulse detection problem is certain. A receiving inspection test may not uncover interference pulses which exist at the measurement site. For solution of this type of problem, see the digital recorder manufacturer's manual or recommendations.

A digital data logger may present different concerns. It may be a device which samples voltages, averages them, and transfers the average to a memory peripheral, either at the site or at the end of a communication link. Conversion to engineering units may occur at almost any point. The routine calibration should look at the output voltage of a signal conditioner as a primary point to assess accuracy of measurement. Analog to digital conversion, averaging and transmission and storage would be expected to degrade the measurement accuracy very little. Such functions should contribute less than 0.05 m/s uncertainty from a voltage input to a stored average value. If greater errors are found when comparing known rates of rotation and known signal conditioning output voltages to stored average wind speed values, check the data logger manual for specifications and trouble-shooting recommendations.

8.3.3 Calibration Data Logs

Site log books must record at least the following:

- Date and time of the calibration period (no valid data)
- Name of calibration person or team members

- Calibration method used (this should identify SOP number and data sheet used)
- Where the data sheet or sheets can be found on site
- Action taken and/or recommended

The data sheet should contain this same information along with the measurement values found and observations made. Model and serial numbers of equipment tested and used for testing must appear. The original report should always be found at the site location and a copy can be used for reports to management (a single-copy carbon form could be used). The truism that "it is impossible to have too many field notes" should be underscored in all training classes for operators and auditors.

8.3.4 Calibration Report

The calibration report may be as simple as copies of the calibration forms with a cover page, summary and recommendations. While the calibration forms kept at the site provide the basis for the operator or the auditor to trace the performance of the instrument system, the copies which become a part of the calibration report provide the basis for management action should such be necessary. The calibration report should travel from the person making out the report through the meteorologist responsible for the determination of data validity to the management person responsible for the project. Any problem should be highlighted with an action recommendation and a schedule for correction. As soon as the responsible management person sees this report the responsibility for correction moves to management, where budget control usually resides. A signature block should be used to document the flow of this information.

8.3.5 Calibration Schedule/Frequency

System calibration and diagnostic checks should be performed at six month intervals, or in accordance with manufacturer's recommendations, whichever is more frequent. The risk of losing data increases with the interval between operational checks. To reduce this risk, routine operational checks should be performed on a daily basis; these daily checks may be performed remotely. On-site inspections and maintenance should be performed on a weekly basis.

8.3.6 Data Correction Based on Calibration Results

Corrections to the raw data are to be avoided. A thorough documentation of an error clearly defined may result in the correction of data (permanently flagged as corrected). For example, if an operator changes the transfer function in a digital logger program and it is subtle enough not to be detected in the quality control inspection of the data stream, but is found at the next calibration, the data may be corrected. The correction can be calculated from the erroneous transfer function and applied to the period starting when the logger program was changed (determined by some objective method such as a log entry) and ending when the error was found and corrected.

Another example might be a damaged anemometer cup or propeller. If an analysis of the data points to the time when the damage occurred, a correction period can be determined. A wind tunnel test will be required to find a new transfer function for the damaged cup or propeller assembly. With the new transfer function defining the true speed responsible for a rate of rotation, and with the assumption that the average period is correctly represented by a steady rate of rotation, a correction can be made and flagged. This is a more risky example and judgment is required since the new transfer function may be grossly different and perhaps non-linear.

8.4 Audits

The audit function has two components, the system audit (in essence, a challenge to the QAPP) and the performance audit (a challenge to the individual measurement systems).

The system audit provides an overall assessment of the commitment to data validity; as such, all commitments made in the QAPP should be subject to challenge. Typical questions asked in the systems audit include: "are standard operating procedures being followed?", "is the station log complete and up-to-date?" All deficiencies should be recorded in the audit report along with an assessment of the likely effect on data quality. Corrective actions related to a systems audit should be obvious if the appropriate questions are asked.

The performance audit is similar to a calibration in terms of the types of activities performed (Section 8.3) - all the performance audit adds is an independent assurance that the calibrations are done correctly and that the documentation is complete and accurate. In the ideal case, when both the auditor and site operator are equally knowledgeable, the auditor functions as an observer while the site operator performs the calibration; in this instance the auditor functions in a "hands-off" mode. In initial audits, since newly hired site operators may have little or no experience with meteorological instruments, the hands-off approach may not be practical or desirable. In these instances, the audit may also function as a training exercise for the site operator.

8.4.1 Audit Schedule and Frequency

An initial audit should be performed within 30 days of the start-up date for the monitoring program. The 30-day period is a compromise between the need for early detection and correction of deficiencies and the time needed for shake-down and training. Follow-up audits should be conducted at six-month intervals.

8.4.2 Audit Procedure

To ensure against conflicts of interest, all audits should be conducted by individuals who are independent of the organizations responsible for the monitoring and/or using the data. This is especially important as the audit will be essential in any legal claims related to data validity. The audit should begin with a briefing stating the goals of the audit and the procedures to be employed - in addition, if any assistance is needed (e.g., in removing a wind vane from a tower)

this would be the time to arrange such with the site technicians. An exit interview should be conducted when the audit is finished; management from the organizations involved should be present at both the initial briefing and the exit interview.

8.4.3 Corrective Action and Reporting

A corrective action program is an essential management tool for coordination of the QAQC process. Activities associated with the corrective action program include: review of procedures for reporting deficiencies, problem tracking, planning and implementing measures to correct problems, and tracking of problem resolution. Documentation of corrective actions is included with other information in support of data validity. A sample form for documenting corrective actions can be found in reference **[65]**.

An audit report should be completed and submitted within 30 days of the audit performance. This is an important document in that it provides a basis for any legal claims to data validity. As such, care should be taken to ensure that all statements related to data validity are supportable. Where possible the report should contain copies of the forms used in the audit.

8.5 Routine and Preventive Maintenance

Data quality is dependent on the care taken in routine and preventative maintenance. These functions are the responsibility of the site technicians; given their important QAQC role, they should be fully trained to maintain the equipment. The training program for the site technicians should be addressed in the QAPP. The following additional information on maintenance should also be included in the QAPP:

- A list the site technicians and their alternates
- Procedures and checklists for preventive maintenance
- Schedule for preventive maintenance
- Procedures for maintaining spare components
- A list of the components to be checked and/or replaced

Checklists are an essential component of a routine maintenance program and should be used as a matter of course. The instrument manuals should be used as the starting point for the checklist for each of instruments - a good manual should indicate what components need to be checked and how often. A station checklist should also be developed; this should include the following:

- A List of safety and emergency equipment.
- List of items to be inspected following severe weather.
- A checkoff to ensure there is adequate disk space for on-site storage of the raw data.

- A checkoff to indicate that backup of data has been completed.
- A checkoff to indicate that clocks have been checked and adjusted as necessary.
- A checkoff for the cables and guy wires securing the equipment.

All routine and preventive maintenance activities should be recorded in the station log and/or on the appropriate checklist. The station log and checklist provide the necessary paper trail to support claims of accuracy.

8.5.1 Standard Operating Procedures

Standard operating procedures (SOPs) should be developed that are specific to the operations at a given site. The purpose of an SOP is to spell out operating and QC procedures with the ultimate goal of maximizing data quality and data capture rates. Operations should be performed according to a set of well defined, written SOPs with all actions documented in logs and on prepared forms. SOPs should be written in such a way that if problems are encountered, instructions are provided on actions to be taken. At a minimum, SOPs should address the following:

- Installation, setup, and checkout
- Site operations and calibrations
- Operational checks and preventive maintenance
- Data collection protocols
- Data validation steps
- Data archiving

8.5.2 Preventive Maintenance

8.5.2.1 Wind Speed

The anemometer has just one mechanical system which will benefit from preventive maintenance. That is the bearing assembly. There are two strategies from which to choose. One is to change the bearings (or the entire instrument if a spare is kept for that purpose) on a scheduled basis and the other is to make the change when torque measurements suggest change is in order. The former is most conservative with respect to data quality assuming that any time a torque measurement indicates a bearing problem, the bearing will be changed as a corrective maintenance action.

As routine calibrations become less frequent (8.3.5), the probability increases that a starting torque measurement will be made which indicates the anemometer is outside its performance specification. This will effect both the threshold (by increasing it) and the transfer function (by moving the non-linear threshold toward high speeds). It is unlikely that corrections can be properly made to the data in this case. The consequence might be the loss of a half-year's

data, if that is the period for routine calibration. If experience indicates that the anemometer bearing assembly shows serious wear at the end of one year or two years (based on torque measurements), a routine change of bearings at that frequency is recommended.

8.5.2.2 Wind Direction

The wind vane usually has two mechanical systems which will benefit from preventive maintenance. The bearing assembly is one and can be considered in the same way as the anemometer bearing assembly described above. The other is the potentiometer which will certainly "wear out" in time. The usual mode of failure for a potentiometer is to become noisy for certain directions and then inoperative. The noisy stage may not be apparent in the average direction data. If σ_A is calculated, the noise will bias the value toward a higher value. It will probably not be possible to see early appearance of noise in the σ_A data. When it becomes obvious that the σ_A is too high, some biased data may already have been validated and archived. Systems with time constant circuits built into the direction output will both mask the noise from the potentiometer (adding to the apparent potentiometer life) and bias the σ_A toward a lower value. Such circuits should not be used if they influence the actual output capability of the sensor. Each manufacturer may be different in their selection of a source and specifications used in buying potentiometers. The operator needs to get an expected life for the potentiometer from the manufacturer and monitor the real life with a noise sensitive test. An oscilloscope is best and can be used without disrupting the measurement. When potentiometer life expectations have been established, a preventive maintenance replacement on a conservative time basis is recommended.

8.5.2.3 Temperature and Temperature Difference

Aspirated radiation shields use fans which will also fail in time. The period of this failure should be several years. The temperature error resulting from this failure will be easily detected by a QC meteorologist inspecting the data. Some aspirated radiation shields include an air flow monitoring device or a current check which will immediately signal a disruption in aspiration. Preventive maintenance is not required but spare fans should be on the shelf so that a change can be made quickly when failure does occur.

8.5.2.4 Dew Point Temperature

Field calibration checks of the dew point temperature measurement system can be made with a high-quality Assmann-type or portable, motor-aspirated psychrometer. Sling psychrometers should not be used. Several readings should be taken at the intake of the aspirator or shield at night or under cloudy conditions during the day. These field checks should be made at least monthly, or in accordance with manufacturer's suggestions, and should cover a range of relative humidity values.

Periodically (at least quarterly) the lithium chloride in dew cells should be removed and recharged with a fresh solution. The sensor should be field-checked as described above before and at least an hour after the lithium chloride solution replacement.

If cooled-mirror type dew point systems are used, follow the manufacturer's service suggestions initially. The quality of the data from this method of measurement is dependent upon the mirror being kept clean. The frequency of service required to keep the mirror clean is a function of the environment in which the sensor is installed. That environment may vary with seasons or external weather conditions. If changes in dew point temperature of a magnitude larger than can be tolerated are found after service scheduled according to the manufacturer's suggestion, increase the service frequency until the cleaning becomes preventive maintenance rather than corrective service. This period will vary and can be defined only by experience. Station log data must include the "as found" and the "as left" measurements. Dew point temperature does not change rapidly (in the absence of local sources of water) and the difference between the two measurements will usually be the instrument error due to a dirty mirror.

8.5.2.5 Precipitation

The gauge should be inspected at regular intervals using a bubble level to see that the instrument base is mounted level. Also, the bubble level should be placed across the funnel orifice to see that it is level. The wind screen should also be checked to see that it is level, and that it is located l/2 inch above the level of the orifice, with the orifice centered within the screen.

8.5.2.6 Pressure

The output of the pressure sensor should be regularly checked against a collocated instrument. A precision aneroid barometer can be used for this check. The collocated barometer should be occasionally checked against a mercurial barometer reading at a nearby NWS station.

8.5.2.7 Radiation

The optical hemispheres on pyranometers and net radiometers should be cleaned frequently (preferably daily) with a soft, lint-free cloth. The surfaces of the hemispheres should be regularly inspected for scratches or cracks. The detectors should be regularly inspected for any discoloration or deformation. The instruments should be inspected during cool temperatures for any condensation which may form on the interior of the optical surfaces.

While calibrations must be done by the manufacturer, radiation can be field-checked using a recently-calibrated, collocated instrument. Since signal processing is particularly critical for these sensors, the collocated instrument should also use its own signal conditioner and data recording system for the check. This kind of field check should be done every six months.

It is mandatory to log "as found" and "as left" information about the parts of the system which seem to require work. Without this information it becomes difficult, if not impossible, to assess what data are usable and what are not.

8.6 Data Validation and Reporting

Data validation is a process in which suspect data are identified and flagged for additional review and corrective action as necessary. The data validation process provides an additional level of quality assurance for the monitoring program. Some problems that may escape detection during an audit (e.g., a wind vane that occasionally gets stuck) are often easily identified during data validation.

Data validation should be performed by a person with appropriate training in meteorology who has a basic understanding of local meteorological conditions and the operating principles of the instruments.

8.6.1 Preparatory Steps

Preparatory steps prior to data validation include: collection and storage of the raw data, backup, data reduction, transfer of data off-site, and preliminary review. These steps are discussed in the following:

- Collection and storage on-site (as appropriate) of the "raw" signals from the sensors, followed by real-time processing of the "raw" data by the data acquisition system to produce reduced, averaged values of the meteorological variables. The reduced data are stored on the data acquisition system's computer, usually in one or more ASCII files.
- Transfer of the reduced data to a central data processing facility at regular intervals (e.g., daily). Once the data are received at the central facility, they should be reviewed by an experienced data technician as soon as possible to verify the operational readiness of the monitoring site. Backup copies of the data should be prepared and maintained on-site and off-site.

Data collected by the monitoring systems can usually be obtained by polling the data system at a site from the central facility using a personal computer, modem, and standard telecommunications software. Other options that are available for communications with a remote site include leased-line telephone service, local or wide area network (LAN, WAN) connections, Internet access, and satellite telemetry. For immediate turnaround of data, the operator can transfer the data to the central facility using a personal computer equipped with a modem and communications software.

8.6.2 Levels of Validation

A level of validation, for the purposes of this guidance, is a numeric code indicating the degree of confidence in the data. These levels provide some commonality among data collected and quality controlled by different agencies, and help ensure that all data have received a comparable level of validation. Various data validation "levels" that apply to air quality and meteorological data have been defined by Mueller and Watson **[66]** and Watson et al. **[67]**. Basically, four levels of data validation have been defined:

- **Level 0** data validation is essentially raw data obtained directly from the data acquisition systems in the field. Level 0 data have been reduced and possibly reformatted, but are unedited and unreviewed. These data have not received any adjustments for known biases or problems that may have been identified during preventive maintenance checks or audits. These data should be used to monitor the instrument operations on a frequent basis (e.g., daily), but should not be used for regulatory purposes until they receive at least Level 1 validation.
- **Level 1** data validation involves quantitative and qualitative reviews for accuracy, completeness, and internal consistency. Quantitative checks are performed by software screening programs (**see Section 8.7.3.2**) and qualitative checks are performed by meteorologists or trained personnel who manually review the data for outliers and problems. Quality control flags, consisting of numbers or letters, are assigned to each datum to indicate its quality. A list of suggested quality control codes is given in Table 8-3. Data are only considered at Level 1 after final audit reports have been issued and any adjustments, changes, or modifications to the data have been made.
- **Level 2** data validation involves comparisons with other independent data sets. This includes, for example, intercomparing collocated measurements or making comparisons with other upper-air measurement systems.
- **Level 3** validation involves a more detailed analysis when inconsistencies in analysis and modeling results are found to be caused by measurement errors.

8.6.3 Validation Procedures

All necessary supporting material, such as audit reports and any site logs, should be readily available for the level 1 validation. Access to a daily weather archive should be provided for use in relating suspect data with to local and regional meteorological conditions. Any problem data, such as data flagged in an audit, should be corrected prior to the level 1 data validation. The validation procedures described in the following include screening, manual review, and comparison.

Table 8-3

Suggested quality control (QC) codes for meteorological data.

Code	Meaning	Description
0	Valid	Observations that were judged accurate within the performance limits of the instrument.
1	Estimated	Observations that required additional processing because the original values were suspect, invalid, or missing. Estimated data may be computed from patterns or trends in the data (e.g., via interpolation), or they may be based on the meteorological judgment of the reviewer.
2	Calibration applied	Observations that were corrected using a known, measured quantity (e.g., instrument offsets measured during audits).
3	Unassigned	Reserved for future use.
4	Unassigned	Reserved for future use.
5	Unassigned	Reserved for future use.
6	Failed automatic QC check	Observations that were flagged with this QC code did not pass screening criteria set in automatic QC software.
7	Suspect	Observations that, in the judgment of the reviewer, were in error because their values violated reasonable physical criteria or did not exhibit reasonable consistency, but a specific cause of the problem was not identified (e.g., excessive wind shear in an adiabatic boundary layer). Additional review using other, independent data sets (Level 2 validation) should be performed to determine the final validity of suspect observations.
8	Invalid	Observations that were judged inaccurate or in error, and the cause of the inaccuracy or error was known (e.g., winds contaminated by ground clutter or a temperature lapse rate that exceeded the autoconvective lapse rate). Besides the QC flag signifying invalid data, the data values themselves should be assigned invalid indicators.
9	Missing	Observations that were not collected.

8.6.3.1 Data Screening

Screening procedures generally include comparisons of measured values to upper and lower limits; these may be physical limits, such as an instrument threshold, or may be established based on experience or historical data. Other types of procedures employed in screening include assessments based on the rate of change of a variable (in these data that change too rapidly or not at all are flagged as suspect) and assessments based on known physical principles relating two or more variables (e.g., the dew point should never exceed the dry-bulb temperature).

Screening may be regarded as an iterative process in which range checks and other screening criteria are revised as necessary based on experience. For example, an initial QA pass of a data set using default criteria may flag values which upon further investigation are determined to be valid for the particular site. In such cases, one or more follow-up QA passes using revised criteria may be necessary to clearly segregate valid and invalid data. Suggested screening criteria are listed in Table 8-4. Data which fail the screening test should be flagged for further investigation.

8.6.3.2 Manual Review

The manual review should result in a decision to accept or reject data flagged by the screening process. In addition, manual review may help to identify outliers that were missed by screening. This review should be performed by someone with the necessary training in meteorological monitoring.

In the typical manual review, data should be scanned to determine if the reported values are reasonable and in the proper format. Periods of missing data should be noted and investigated. Data should also be evaluated for temporal consistency. This is particularly useful for identifying outliers in hourly data. Outliers should be reviewed with reference to local meteorological conditions. Data are considered to be at Level 1 validation following the manual review and can be used for modeling and analysis.

8.6.3.3 Comparison Program

After the data have passed through the screening program, they should be evaluated in a comparison program. Randomly selected values should be manually compared with other available, reliable data (such as, data obtained from the nearest National Weather Service observing station). At least one hour out of every 10 days should be randomly selected. To account for hour-to-hour variability and the spatial displacement of the NWS station, a block of several hours may be more desirable. All data selected should be checked against corresponding measurements at the nearby station(s). In addition, monthly average values should be compared with climatological normals, as determined by the National Weather Service from records over a 30-year period. If discrepancies are found which can not be explained by the geographic difference in the measurement locations or by regional climatic variations, the data should be flagged as questionable.

Table 8-4

Suggested Data Screening Criteria

Variable	Screening Criteria: Flag data if the value
Wind Speed	- is less than zero or greater than 25 m/s
	- does not vary by more than 0.1 m/s for 3 consecutive hours
	- does not vary by more than 0.5 m/s for 12 consecutive hours
Wind Direction	- is less than zero or greater than 360 degrees
	- does not vary by more than 1 degree for more than 3 consecutive hours
	- does not vary by more than 10 degrees for 18 consecutive hours
Temperature	- is greater than the local record high
	- is less than the local record low
	(The above limits could be applied on a monthly basis.)
	- is greater than a 5°C change from the previous hour
	- does not vary by more than 0.5°C for 12 consecutive hours
Temperature Difference	- is greater than 0.1°C/m during the daytime
	- is less than -0.1°C/m during the night time
	- is greater than 5.0°C or less than -3.0°C
Dew Point Temperature	- is greater than the ambient temperature for the given time period
	- is greater than a 5°C change from the previous hour
	- does not vary by more than 0.5°C for 12 consecutive hours
	- equals the ambient temperature for 12 consecutive hours
Precipitation	- is greater than 25 mm in one hour
	- is greater than 100 mm in 24 hours
	- is less than 50 mm in three months
	(The above values can be adjusted based on local climate.)
Pressure	- is greater than 1060 mb (sea level)
	- is less than 940 mb (sea level)
	(The above values should be adjusted for elevations other than sea level.)
	- changes by more than 6 mb in three hours
Radiation	- is greater than zero at night
	- is greater than the maximum possible for the date and latitude

8.6.3.4 Further Evaluations

Any data which are flagged by the screening program or the comparison program should be evaluated by personnel with meteorological expertise. Decisions must be made to either accept the flagged data, or discard and replace it with back-up or interpolated data, or data from a nearby representative monitoring station (see Section 1). Any changes in the data due to the validation process should be documented as to the reasons for the change. If problems in the monitoring system are identified, corrective actions should also be documented. Any edited data should continue to be flagged so that its reliability can be considered in the interpretation of the results of any modeling analysis which employs the data.

8.6.4 Schedule and Reporting

Data should be retrieved on a daily basis and reviewed for reasonableness to ensure that the instrument is operating properly. Level 1 data validation should be performed as frequently as possible (e.g., bi-weekly or monthly). At a minimum, validation should be done weekly for the first month after the instrument is installed, so that any potential problems can be identified and quickly resolved to avoid significant data losses.

It is important to maintain detailed, accurate records of changes to the data and the data quality control codes. These records will save time and effort if questions arise about specific data at a later date. Reports should include the following information:

- Who performed the quality control validation, type of data validated, and when the validation was completed.
- Any adjustments, deletions, or modifications, with a justification or reason for the change.
- Identification of data points that were flagged as suspect or invalid, and the reason why they were flagged.
- Systematic problems that affected the data.

8.7 Recommendations

Quality Assurance/Quality Control (QAQC) procedures should be documented in a Quality Assurance Project Plan (QAPP) and approved by the appropriate project or organizational authority. These procedures should provide quantitative documentation to support claims of accuracy and should be conducted by persons independent of the organization responsible for the collection of the data and the maintenance of the measurement systems.

Procurement documents for meteorological monitoring systems should include the specifications for instrument systems and should identify the test method by which conformance with the specification will be determined. Persons responsible installing meteorological systems should review documentation provided on conformance-testing and should conduct independent

acceptance tests to verify claims of accuracy. All acceptance-testing activities should be documented in the station log.

Routine system calibrations and system audits should be performed at the initiation of a monitoring program (within 30 days of start-up) and at least every six months thereafter. More frequent calibrations and audits may be needed in the early stages of the program if problems are encountered, or if valid data retrieval rates are unacceptably low. Documentation of all calibrations should include a description of the system "as found", details of any adjustments to the instrument, and a description of the system "as left"; this documentation is necessary for any claims of data validity.

Regular and frequent routine operational checks of the monitoring system are essential to ensuring high data retrieval rates. These should include visual inspections of the instruments for signs of damage or wear, inspections of recording devices to ensure correct operation and periodic preventive maintenance. The latter should include periodic checks of wind speed and wind direction bearing assemblies, cleaning of aspirated shield screens in temperature systems, removal and recharging (at least quarterly) of lithium chloride dew cells, cleaning of the mirror in cooled mirror dew cells, clearing the precipitation gauge funnel of obstructing debris, and frequent (preferably daily) cleaning of the optical surface of a pyranometer or net radiometer. Also crucial to achieving acceptable valid data retrieval rates is the regular review of the data by an experienced meteorologist. This review should include visual scanning of the data, and automated screening and comparison checks to flag suspect data. This review should be performed weekly, and preferably on a daily basis.

9. UPPER-AIR MONITORING

This section provides guidance for the most widely used technologies employed for monitoring upper-air meteorological conditions; these include radiosondes and ground-based remote sensing platforms: sodar (Sound Detection and Ranging), radar (Radio Detection and Ranging), and RASS (Radio Acoustic Sounding System). While they are not covered in detail, other (emerging) technologies such as lidar (Light Detection and Ranging) may provide alternative means for the collection of upper-air meteorological data.

The material is organized such that information necessary to the understanding of the technology (Sections 9.1 through 9.3) precedes the guidance (Sections 9.4 through 9.7). The sections are as follows: Section 9.1 provides information necessary to the understanding of balloon-based sounding instruments and ground-based remote sensing technologies. Section 9.2 provides information on the performance characteristics of these systems; Section 9.3 discusses monitoring objectives and goals for monitoring of the boundary layer in support of air quality dispersion modeling; Section 9.4 provides guidance on siting and exposure of upper-air monitoring systems; Section 9.5 provides guidance on installation and acceptance testing; Section 9.6 provides guidance on quality assurance; and Section 9.7 provides guidance for data processing and management.

9.1 Fundamentals

Table 9-1 provides an overview of the upper-air monitoring systems included in this guidance. Necessary details describing the operation of each of the monitoring platforms [Radiosonde (9.1.2), Doppler Sodar (9.1.3), Radar Wind Profiler (9.1.4), and RASS (9.1.5)] is preceded by a description of the various meteorological variables that are measured by, or derived from measurements obtained with these platforms

9.1.1 Upper-Air Meteorological Variables

Meteorological variables measured/reported in upper-air monitoring programs include wind direction, wind speed, pressure, temperature, and humidity. With some exceptions (e.g., radiosonde measurements of pressure, temperature, and humidity), the upper-air data for these variables are based on indirect measurements; i.e., the desired variable is derived from measurements of other variables which are measured directly. This is a significant difference from the in situ measurements of these variables; i.e., when monitored in situ (such as from a meteorological tower) these variables are measured directly. This difference has significant implications for calibrations and audits of upper-air measurement systems (see Section 9.6).

Fundamentals related to upper-air monitoring of wind, pressure, temperature, and humidity are presented in the following. This is followed by information on estimating mixing heights and stability for use in dispersion modeling. Although the latter are often included in discussions of upper-air meteorological conditions, they are not really upper-air variables; a more

accurate classification of mixing height would describe it as a boundary layer variable which can be derived from upper-air measurements. Stability, as defined for use in dispersion modeling, is a surface layer variable and is not necessarily related to or correlated with upper-air measurements.

Wind Upper-air wind speeds and wind directions are vector-averaged measurements. None of the measurement systems described in the following sections provide a means to measure winds as scaler quantities, as is done with cup and vane sensors mounted on an instrumented tower. While tower-based measurements near the surface are easily obtained, there are very few instrumented tall towers that can provide vertical profiles of upper-air winds over the altitudes needed for some air quality applications.

Upper-air wind data comprise either path averages (radiosondes) or volume averages (remote sensors) rather than point measurements. For air quality programs, where the interest is mainly to characterize winds in the atmospheric boundary layer (ABL) and lower troposphere, radiosonde data are typically averaged over vertical layers with a depth of approximately 45 to 75 meters (m). Wind data provided by sodars are typically averaged over layers that are 5 to 100 m deep, while radar wind profiler data are usually averaged over 60 to 100 meter intervals. The altitude at which the winds are reported is assumed to be the mid-point of the layer over which the winds are averaged. Averaging periods for upper-air wind data also vary depending on the instrument system used. An individual wind data report from a radiosonde sounding system is typically averaged over no more than 30 to 120 seconds, representing averages of 60 to 700 meters. The averaging interval for winds measured by sodars and radar profilers is usually on the order of 15 to 60 minutes.

Upper-air wind data are needed to accurately characterize upper-air transport. For example, observing and resolving the vertical shear of the horizontal wind (both speed and directional changes with height) can be important for air quality model applications. Figure 9-1 shows a plot of upper-air winds measured by a radiosonde sounding system, along with simultaneous profiles of temperature, dew-point temperature, and potential temperature. The wind data are represented in the “wind barb” format, in which the direction of the wind is indicated by the orientation of an arrow's shaft (relative to true north, which is toward the top of the figure), and the wind speed is indicated by the number and length of barbs attached to the shaft. Note the change in wind speed and direction that is evident in the first few hundred meters of the sounding. In this case, below about 280 meters the winds are east-southeasterly. Above this level the winds veer (turn clockwise) with height to become southerly, southwesterly, then westerly. This is a simple example of a pattern that is common in upper-air measurements; in fact, much more complex wind shear conditions are often observed. Wind shear conditions can have important implications with respect to air quality, because of the different transport and turbulence conditions that can exist at different altitudes where air pollutants may be present.

Shear patterns such as those depicted in Figure 9-1 occur in part because of the frictional drag exerted on the atmosphere by the earth's surface. The atmospheric boundary layer is generally defined as the layer of the atmosphere within which the dynamic properties (i.e., winds) and thermodynamic properties (i.e., temperature, pressure, moisture) are directly influenced by the earth's surface. Factors that influence the vertical distribution of winds include horizontal

gradients in temperature (thermal wind effects), the development of local temperature and pressure gradients in shoreline settings (land/sea-breeze circulations) and complex terrain environments (mountain-valley airflows), vertical momentum transport by turbulent eddies, and diurnal reductions in frictional stress at night that can lead to the formation of low-level jets. Processes such as these are described in references **[68]** and **[69]**; examples of the effects of such circulations on air quality are described in reference **[70]**.

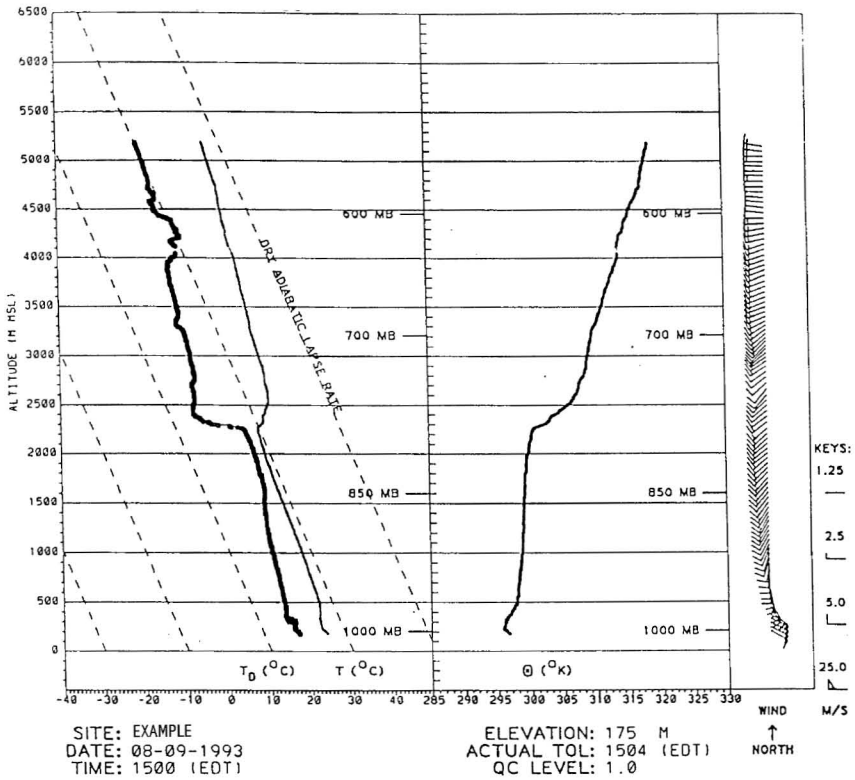

Figure 9-1 Example wind and temperature profiles from a radiosonde sounding system.

Consequently, upper-air wind data are critical to air quality analysis and modeling efforts. The data are used for the assessment of transport characteristics, as direct input to Gaussian dispersion models, and in the initialization and application of meteorological models (that are used to prepare time-varying, three-dimensional meteorological fields for puff and grid-based air quality models).

Upper-air wind speeds are almost always reported in units of meters per second (ms^{-1}) or knots (nautical miles per hour). Wind direction is reported as the direction from which the wind is blowing in degrees (clockwise) relative to true north. Altitude is usually reported in meters or feet and must be defined as corresponding to height above mean sea level or height above ground

level. Radiosonde data are typically reported as height above mean sea level (msl), whereas wind data collected by the remote sensing systems are often reported as height above ground level (agl).

Some remote sensing systems described in these guidelines provide a measure of vertical velocity. To date, however, little use has been made of these data in air quality modeling or data analysis applications. Additional work is needed (possibly on a case-by-case basis) to determine the utility of these data for air quality applications.

Pressure Vertical profiles of atmospheric pressure are measured during radiosonde ascents. The remote sensing systems considered in this document do not measure pressure. Pressure data are critical for radiosonde soundings because they are used to calculate the altitude of the sonde (strictly speaking, the geopotential altitude). Differential global position systems (GPS) rawinsonde systems are being developed that will be able to measure the altitude of the sonde directly, but pressure data will still be needed to support many modeling and data analysis efforts. For air quality purposes, pressure data are used in the application of meteorological models, and as direct input to air quality models. Pressure is reported in units of millibars (mb) or hectopascals (hPa).

Temperature Upper-air temperature measurements are most commonly obtained using radiosonde sounding systems. Radiosonde temperature measurements are point measurements. These can be obtained every few seconds, yielding a vertical resolution of a few meters to about 10 m, depending on the rate of ascent of the balloon.

Temperature data can also be obtained using RASS. RASS temperature measurements are volume averages, with a vertical resolution comparable to that of the wind measurements reported by the remote sensing systems (i.e., 50 to 100 m). RASS measures the virtual temperature (T_v) of the air rather than the dry-bulb temperature (T). The virtual temperature of an air parcel is the temperature that dry air would have if its pressure and density were equal to those of a parcel of moist air, and thus T_v is always higher than the dry-bulb temperature. Under hot and humid conditions, the difference between T_v and T is usually on the order of a few (2 to 3) degrees C; at low humidity, differences between T_v and T are small. Given representative moisture and pressure profiles, temperature can be estimated from the virtual temperature measurements.

Temperature data are used widely in air quality analysis and modeling, including the application and evaluation of meteorological models, and as direct input to air quality models. The vertical temperature structure (stability) influences plume rise and expansion and thus the vertical exchange of pollutants. Temperature also affects photolysis and chemical reaction rates. Temperature is reported in degrees Celsius (°C) or Kelvins (K).

Moisture Like pressure, upper-air moisture measurements suitable for air quality applications are primarily obtained using radiosonde sounding systems. The sampling frequency and vertical and temporal resolution of the moisture data are the same as the other thermodynamic variables measured by these systems. Moisture is most commonly measured directly as relative humidity (RH), and is reported as percent RH or as dew-point temperature (T_d) in °C (or frost point temperature). Dew-point depression, the difference between

temperature and dew-point temperature ($T - T_d$), is also a commonly reported variable. Some radiosonde sounding systems measure the wet-bulb temperature instead, and determine RH and dew-point temperature through the psychrometric relationship.

Upper-air moisture profiles are used in the initialization and application of meteorological models, and as direct input to air quality models. Moisture data can be important to a successful meteorological modeling effort, because the accurate simulation of convective development (clouds, precipitation, etc.) depends on an accurate representation of the three-dimensional moisture field. Upper-air moisture data are also useful to the understanding of the formation and growth of aerosols, which grow rapidly at high relative humidity (90 to 100 percent).

Mixing Height For the purposes of this guidance, mixing height is defined as the height of the layer adjacent to the ground over which an emitted or entrained inert non-buoyant tracer will be mixed (by turbulence) within a time scale of about one hour or less (adapted from Beyrich **[43]** . This concept of a mixing height was first developed for characterizing dispersion in a daytime convective boundary layer (CBL). Since tracer measurements are impractical for routine application, alternative methods are recommended for estimating mixing heights based on more readily available data (Table 9-2). The Holzworth method **[44]** is recommended for use when representative NWS upper-air data are available. This procedure relies on the general theoretical principle that the lapse rate is roughly dry adiabatic (no change in potential temperature with height) in a well-mixed daytime convective boundary layer (CBL); the Holzworth method is described in Section 6.5.1. Other alternatives include using estimates of mixing heights provided in CBL model output (references **[45]** and **[46]**). Mixing heights derived from remote sensing measurements of turbulence or turbulence related parameters are discussed in the following.

Turbulence, or turbulence related measurements (e.g, backscatter measurements from a sodar or refractive index measurements from a radar wind profiler) though not surrogates for an inert tracer can sometimes be used to estimate mixing heights since, under certain conditions, such measurements correlate with the top of the mixed layer. In looking at these measurements, one attempts to determine depth of the layer adjacent to the surface within which there is continuous or intermittent turbulence; this is a non-trivial exercise since turbulence varies considerably, not only with height, but with time and location. This variability is dependent upon which processes control/dominate the production of turbulence near the surface; these processes are discussed in the following.

The production of turbulent eddies during the daytime is dominated (under clear sky conditions) by heating of the ground surface and (under overcast conditions) by frictional drag. Daytime vertical mixing processes can be vigorous (especially under convective -conditions) and can produce a well mixed or nearly uniform vertical concentration profile of an inert tracer. During the nighttime, there are several processes that contribute to the production of turbulence including wind shear (created near the ground by friction), variations in the geostrophic wind, and the presence of a low-level jet (wind shear both below and above the jet can enhance turbulence). Nighttime vertical mixing processes are typically patchy and intermittent, and not capable of producing a well-mixed uniform vertical concentration profile.

Table 9-2

Methods for Determining Mixing Heights

Platform	Variable Measured	Advantages/limitations
Aircraft LIDAR	Inert tracer	Consistent with the definition of mixing height as used in dispersion modeling. Labor intensive, not practical for routine applications.
Rawinsonde	Potential temperature	A relatively robust technique for estimating the daytime (convective) mixing depth. Limited by the non-continuous nature of rawinsonde launches.
Sodar	Turbulence Acoustic backscatter	Used for continuous monitoring of boundary layer conditions. The range of a sodar, however, is limited; estimates of the mixing height are possible only when the top of the mixed layer is within the range of the sodar. A good tool for monitoring the nocturnal, surface-based temperature inversion - although different from the mixing height, the nocturnal inversion is equally important for modeling nocturnal dispersion conditions.
Radar wind profiler	Refractive index	Used for continuous monitoring of boundary layer conditions.
RASS	Virtual temperature	The virtual temperature profile obtained using a RASS is used to estimate the convective mixing height in the same manner that temperature data are used (limited to the range of the RASS ≈ 1 km..).

Wind turbulence parameters and/or acoustic backscatter profiles derived from sodar data can also be used to estimate mixing height. These data can be used for both daytime and nighttime conditions, but only when the top of the mixing height is within the range of the sodar.

The refractive index structure parameter (C_n^2) calculated from radar wind profiler reflectivity measurements can also be used to estimate mixing height **[71]**. During nighttime hours, however, the mixing height may be below the range of the radar wind profile.

The virtual temperature profile obtained using a RASS instrument can be used to estimate convective mixing height in the same manner that temperature data are used; this is possible only when the mixing height is within the range of the RASS.

Turbulence Some sodars report wind turbulence parameters. In using these parameters, one must remember that sodars measure the vector components of the wind. Furthermore, there may be significant differences in time and space between the sampling of the components so that any derived variables using more than one component may be affected by aliasing. Thus, the derived turbulence parameters from sodars are generally not the same parameters that models expect for input. Numerous studies have been performed comparing sodar-based turbulence

statistics with tower-based turbulence statistics. Findings from these studies have generally shown that measurements of the standard deviation of the vertical component of the wind speed (σ_w) are in reasonable agreement , while the standard deviation calculations incorporating more than one component (e.g., σ_θ) are not **[72]**. It is therefore recommended that, unless models are designed to use sodar-type statistical parameters, the use of derived turbulence parameters be limited to single component calculations such as σ_w. Note however that the utility of σ_w will depend upon the resolution of the sodar system.

9.1.2 Radiosonde Sounding System

Radiosonde sounding systems use *in situ* sensors carried aloft by a small, balloon-borne instrument package (the radiosonde, or simply "sonde") to measure vertical profiles of atmospheric pressure, temperature, and moisture (relative humidity or wet bulb temperature) as the balloon ascends. In the United States, helium is typically used to inflate weather balloons. Hydrogen is also used. The altitude of the balloon is typically determined using thermodynamic variables or through the use of satellite-based Global Positioning Systems (GPS). Pressure is usually measured by a capacitance aneroid barometer or similar sensor. Temperature is typically measured by a small rod or bead thermistor. Most commercial radiosonde sounding systems use a carbon hygristor or a capacitance sensor to measure relative humidity directly, although a wet-bulb sensor is also used by some systems. With a wet bulb, relative humidity and dewpoint are calculated from psychrometric relationships. Ventilation of the sensors occurs as the balloon rises. The temperature sensor is usually coated to minimize radiational heating effects. The humidity sensor is usually shielded in a ventilated duct inside the sonde's enclosure to minimize exposure to solar radiation.

A radiosonde includes electronic subsystems that sample each sensor at regular intervals (e.g., every 2 to 5 seconds), and transmit the data to a ground-based receiver and data acquisition system. Power for the radiosonde is provided by small dry-cell or wet-cell batteries. Most commercial radiosonde systems operate at 404 MHZ or 1680 MHZ. Once the data are received at the ground station, they are converted to engineering units based on calibrations supplied by the manufacturer. The data acquisition system reduces the data in near-real time, calculates the altitude of the balloon, and computes wind speed and direction aloft based on information obtained by the data systems on the position of the balloon as it is borne along by the wind. Commercial systems available today are relatively compact and easy to operate. The radiosondes are typically smaller than a shoebox and weigh only a few hundred grams. Thus, the previous need to use a parachute to slow the radiosonde's descent after the balloon has burst has greatly diminished, although the manufacturer should still be consulted on this matter. The data systems are either personal computer (PC)-based, or self-contained with standard PC-type computer interfaces for data communications (e.g., RS-232). Data are stored on conventional PC-type hard disks and/or diskettes.

Upper-air winds (horizontal wind speed and direction) are determined during radiosonde ascents by measuring the position of the radiosonde relative to the earth's surface as the balloon ascends. By measuring the position of the balloon with respect to time and altitude, wind vectors can be computed that represent the layer-averaged horizontal wind speed and wind direction for

successive layers. The position data have typically been obtained using radio direction finding techniques (RDF) or one of the radio navigation (NAVAID) networks. The use of satellite-based GPS is becoming more common.

RDF systems use a tracking device called a radio theodolite to measure the position of the balloon relative to the ground station. The radio theodolite, which resembles a small tracking radar system, measures the azimuth and elevation angles to the radiosonde relative to the ground station. The radio theodolite automatically follows the motion of the balloon by tracking the primary lobe of the radiosonde's transmitter, making adjustments to the tilt and pointing direction of the antenna as it follows the signal from the sonde. The azimuth, elevation, and altitude information is then used by the data system to compute the length and direction of a vector projected onto the earth's surface that represents the resultant motion of the balloon over some suitable averaging period, typically 30 to 120 seconds.

With NAVAID systems, the radiosonde's position is determined by triangulation relative to the locations of the fixed NAVAID transmitters. The radiosonde and ground station have electronic subsystems to measure the time delay in the transmissions from the NAVAID sites and to convert this information into the relative motion of the radiosonde, from which winds aloft are computed.

GPS is a satellite navigation system, which is funded and controlled by the U.S. Department of Defense. The system was designed for and is operated by the U.S. military. GPS provides specially coded satellite signals that can be processed in a GPS receiver, enabling the receiver to compute position, velocity and time. GPS wind-finding system sondes consist of a 10-channel GPS (Global Positioning System) receiver as well as a platform for temperature, RH and pressure sensors.

The basic steps in performing a sounding involve: preparing the radiosonde (deploying the sensors, connecting the batteries, etc.); activating the data acquisition system and manually or automatically entering the radiosonde calibration information; inflating the balloon and attaching the sonde; releasing the balloon and activating the tracking system; monitoring the data during the sounding; and performing post-sounding procedures as required (e.g., completing sounding documentation, preparing backups of the data, transferring the data to a central data processing facility, etc.). For air quality programs, the entire procedure requires approximately one hour, and one to two operators. Prior to the release of the radiosonde, an accurate measurement must be made of the surface pressure to provide a baseline value for computing altitude from the radiosonde data. This baseline value is used to compute any offsets that are needed for the sonde's pressure measurements. A good quality barometer that is regularly calibrated and audited should be used to make this measurement. Other baseline readings that should be taken include temperature and moisture (wet bulb or relative humidity), and surface winds, although these data are typically not used to offset the sonde measurements.

High quality tracking information is necessary for obtaining high quality wind data within the atmospheric boundary layer. For monitoring programs with a strong emphasis on characterizing low-level boundary layer winds, it is important that the radio theodolite operator get the theodolite to “lock on” to the radiosonde transmission right from the moment of launch. Otherwise, a few minutes of wind data may be lost while the system acquires the signal and

begins tracking the radiosonde automatically. Due to this type of delay, for example, typical National Weather Service (NWS) data collection procedures result in a smoothing of the winds within approximately the lowest 300 m. With NAVAID systems, it is important to ensure that position information is being acquired prior to release of the balloon. At some sites, high terrain or other obstacles may block the NAVAID radio signals, so that the balloon must be airborne for a few minutes before accurate position information is available. This, too, can cause a few minutes of wind data to be lost at the beginning of a sounding. Normally autonomous (single receiver) GPS position data are only accurate to about 100 meters due to the use of selective availability by the military to introduce an "uncertainty" into the signal. To compensate for this error, the meteorological sounding systems use the base (receiving) station as a differential GPS location which can increase GPS accuracy to better than 1 meter. The horizontal drift of the radiosonde from the release location may also result in the incomplete characterization of the vertical structure of small (spatial and or temporal) scale features.

Generally speaking, radiosonde soundings made for boundary layer air quality studies do not need to achieve the kind of high altitude coverage required for soundings made by the NWS, where data to the tropopause and to stratospheric levels are needed for weather forecasting. For most air quality studies, the vertical range for radiosonde data will not need to exceed 10,000 m msl (approximately 300 mb), and data coverage to 5000 m msl (approximately 500 mb) will be sufficient. In this case, a smaller weather balloon than that used by the NWS, e.g., a 100-gram balloon as opposed to a 300- to 600-gram balloon, is adequate. Balloon size is stated as weight rather than diameter because the weight relates directly to the amount of free lift needed to achieve the desired ascent rate during a sounding, which in turn influences how much helium must be used and, therefore, the cost per sounding.

In a compromise between adequate ventilation of the temperature and moisture sensors on the sonde and good vertical resolution in the boundary layer, ascent rates used for soundings made during air quality studies (2 to 3 ms^{-1}) are also typically less than that used by the NWS (5 to 6 ms^{-1}). As noted earlier, these ascent rates are consistent with an elapsed time of approximately one hour. Thus, the vertical resolution of the thermodynamic data is usually 5 to 10 m, depending on the interval at which the data acquisition system samples the signals from the radiosonde and the time response of the sensor. The vertical resolution of the wind data ranges from approximately 45 to 200 m, depending on the type of sounding system used. The data averaging interval for radiosondes is 1 to 2 minutes in the lower part of a sounding (e.g., lowest 3000 m) and approximately 3 to 4 minutes in the upper part of a sounding.

9.1.3 Doppler Sodar

Commercial sodars operated for the purpose of collecting upper-air wind measurements consist of antennas that transmit and receive acoustic signals. A mono-static system uses the same antenna for transmitting and receiving, while a bi-static system uses separate antennas. The difference between the two antenna systems determines whether atmospheric scattering by temperature fluctuations (in mono-static systems), or by both temperature and wind velocity fluctuations (in bi-static systems) is the basis of the measurement. The vast majority of sodars in use are of the mono-static variety due to their more compact antenna size, simpler operation, and

generally greater altitude coverage. Figure 9-2 shows the beam configurations of mono-static and bi-static systems.

Mono-static antenna systems can be divided into two categories: those using multiple axis, individual antennas and those using a single phased-array antenna. The multiple-axis systems generally use three individual antennas aimed in specific directions to steer the acoustic beam. One antenna is generally aimed vertically, and the other two are tilted slightly from the vertical at an orthogonal angle. Each of the individual antennas may use a single transducer focused into a parabolic dish, or an array of speaker drivers and horns (transducers) all transmitting in-phase to form a single beam. Both the tilt angle from the vertical and the azimuth angle of each antenna need to be measured when the system is set up. Phased-array antenna systems use a single array of speaker drivers and horns (transducers), and the beams are electronically steered by phasing the transducers appropriately. To set up a phased-array antenna, one needs to measure the pointing direction of the array and ensure that the antenna is either level or oriented as specified by the manufacturer.

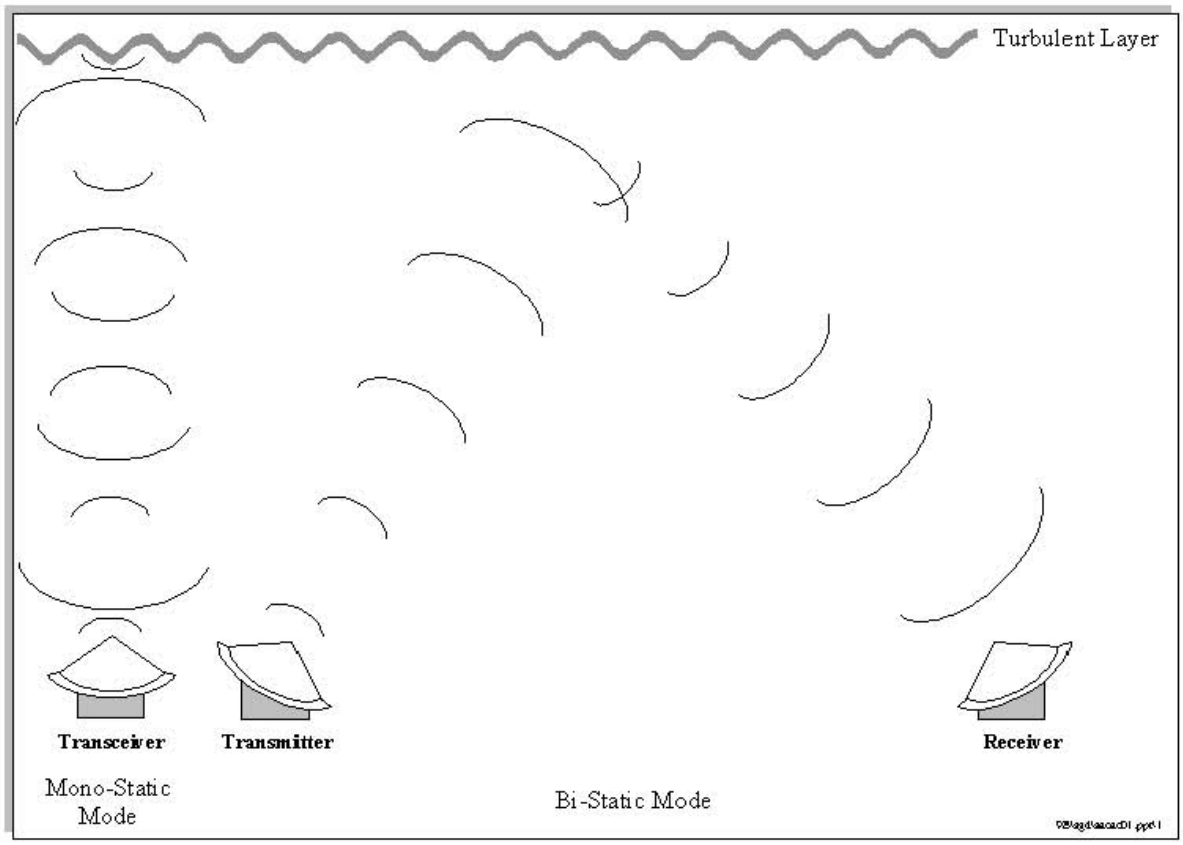

Figure 9-2 Simple depiction of a monostatic and bistatic sodar.

The horizontal components of the wind velocity are calculated from the radially measured Doppler shifts and the specified tilt angle from the vertical. The tilt angle, or zenith angle, is generally 15° to 30°, and the horizontal beams are typically oriented at right angles to one another. Since the Doppler shift of the radial components along the tilted beams includes the influence of both the horizontal and vertical components of the wind, a correction for the vertical velocity should be applied in systems with zenith angles less than 20°. In addition, if the system is located in a region where expected vertical velocities may be greater than about 0.2 ms^{-1}, corrections for the vertical velocity should be made regardless of the beam's zenith angle.

The vertical range of sodars is approximately 0.2 to 2 kilometers (km) and is a function of frequency, power output, atmospheric stability, turbulence, and, most importantly, the noise environment in which a sodar is operated. Operating frequencies range from less than 1000 Hz to over 4000 Hz, with power levels up to several hundred watts. Due to the attenuation characteristics of the atmosphere, high power, lower frequency sodars will generally produce greater height coverage. Some sodars can be operated in different modes to better match vertical resolution and range to the application. This is accomplished through a relaxation between pulse length and maximum altitude, as explained in Section 9.1.4 for radar wind profilers.

Sodar systems should include available options for maximizing the intended capabilities (e.g., altitude range, sampling resolution, averaging time) of the system and for processing and validating the data. The selection of installation site(s) should be made in consultation with the manufacturer and should consider issues associated with the operation of the sodar instrument. Training should be obtained from the manufacturer on the installation, operation, maintenance, and data validation. Additional information on these issues is provided in Section 9.5 of this document.

9.1.4 Radar Wind Profiler

Operating characteristics of three common types of radar wind profilers are given in Table 9-3. The categories included in the table are: 1) very high frequency (VHF) profilers that operate at frequencies near 50 MHZ; 2) ultra-high frequency (UHF) tropospheric profilers that operate at frequencies near 400 MHZ; and 3) UHF lower tropospheric profilers that operate at frequencies near 1000 MHZ. The guidance provided herein is intended for radar wind profilers that fall into the third category; i.e., UHF lower tropospheric profilers (also called boundary layer radar wind profilers).

Doppler radar wind profilers operate using principles similar to those used by Doppler sodars, except that electromagnetic (EM) signals are used rather than acoustic signals to remotely sense winds aloft. Figure 9-3 shows an example of the geometry of a UHF radar wind profiler equipped with a RASS unit (see Section 9.1.5). In this illustration, the radar can sample along each of five beams: one is aimed vertically to measure vertical velocity, and four are tilted off vertical and oriented orthogonal to one another to measure the horizontal components of the air's motion. A UHF profiler includes subsystems to control the radar's transmitter, receiver, signal processing, and RASS (if provided), as well as data telemetry and remote control.

Detailed information on profiler operation can be found in references **[73]** and **[74]**; a brief summary of the fundamentals is provided in the following. The radar transmits an electromagnetic pulse along each of the antenna's pointing directions. The duration of the transmission determines the length of the pulse emitted by the antenna, which in turn corresponds to the volume of air illuminated (in electrical terms) by the radar beam. Small amounts of the transmitted energy are scattered back (referred to as backscattering) toward and received by the radar. Delays of fixed intervals are built into the data processing system so that the radar receives scattered energy from discrete altitudes, referred to as range gates. The Doppler frequency shift of the backscattered energy is determined, and then used to calculate the velocity of the air toward or away from the radar along each beam as a function of altitude. The source of the backscattered energy (radar "targets") is small-scale turbulent fluctuations that induce irregularities in the radio refractive index of the atmosphere. The radar is most sensitive to scattering by turbulent eddies whose spatial scale is ½ the wavelength of the radar, or approximately 16 centimeters (cm) for a UHF profiler.

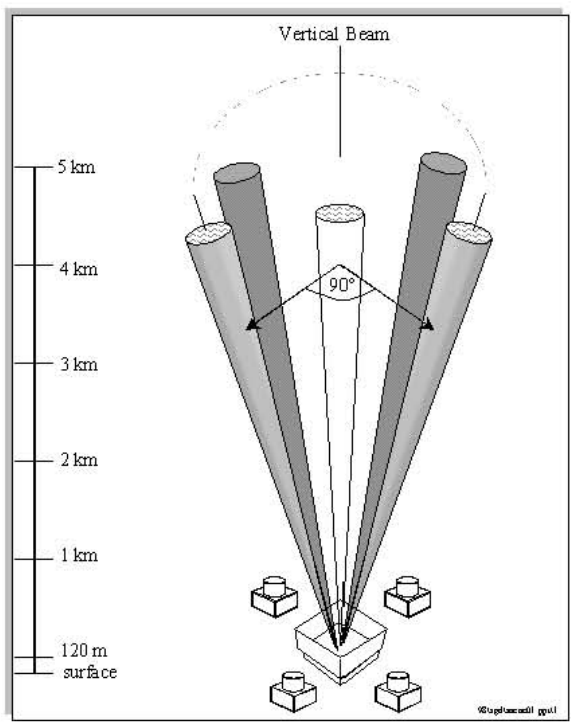

Figure 9-3 Schematic of sampling geometry for a radar wind profiler with RASS.

Table 9-3

Characteristics of radar wind profilers

Frequency Class	Antenna Size (m^2)	Peak Power (kw)	Range (km)	Resolution (m)	Alias and Prototypes
50 MHZ	10,000	250	2-20	150-1000	Alias: VHF radar wind profiler Prototype: 50 MHZ (600 cm) profiler used in the Colorado Wind Profiler Network in 1983.
400 MHZ	120	40	0.2-14	250	Alias: UHF (tropospheric) radar wind profiler Prototypes: 404 MHZ (74 cm) profiler developed for the Wind Profiler Demonstration Network (WPDN) in 1988. 449 MHZ (67 cm) profiler operates at the approved frequency for UHF profilers and will eventually replace the 404 MHZ units. 482 MHZ (62 cm) profiler used by the German Weather Service.
1000 MHZ	3-6	0.5	0.1-5	60-100	Alias: UHF lower-tropospheric radar wind profiler Boundary layer radar wind profiler Lower-atmospheric radar wind profiler Prototypes: 915 MHZ (33 cm) profiler used in the Colorado Wind Profiler Network in 1983. 1290 MHZ (23 cm) boundary layer profiler used by the German Weather Service.

A profiler's (and sodar's) ability to measure winds is based on the assumption that the turbulent eddies that induce scattering are carried along by the mean wind. The energy scattered by these eddies and received by the profiler is orders of magnitude smaller than the energy transmitted. However, if sufficient samples can be obtained, then the amplitude of the energy scattered by these eddies can be clearly identified above the background noise level, then the mean wind speed and direction within the volume being sampled can be determined.

The radial components measured by the tilted beams are the vector sum of the horizontal motion of the air toward or away from the radar and any vertical motion present in the beam. Using appropriate trigonometry, the three-dimensional meteorological velocity components (u,v,w) and wind speed and wind direction are calculated from the radial velocities with corrections for vertical motions. A boundary-layer radar wind profiler can be configured to compute averaged wind profiles for periods ranging from a few minutes to an hour.

Boundary-layer radar wind profilers are often configured to sample in more than one mode. For example, in a “low mode,” the pulse of energy transmitted by the profiler may be 60 m in length. The pulse length determines the depth of the column of air being sampled and thus the vertical resolution of the data. In a “high mode,” the pulse length is increased, usually to 100 m or greater. The longer pulse length means that more energy is being transmitted for each sample, which improves the signal-to-noise ratio (SNR) of the data. Using a longer pulse length increases the depth of the sample volume and thus decreases the vertical resolution in the data. The greater energy output of the high mode increases the maximum altitude to which the radar wind profiler can sample, but at the expense of coarser vertical resolution and an increase in the altitude at which the first winds are measured. When radar wind profilers are operated in multiple modes, the data are often combined into a single overlapping data set to simplify post-processing and data validation procedures.

9.1.5 RASS

The principle of operation behind RASS is as follows: Bragg scattering occurs when acoustic energy (i.e., sound) is transmitted into the vertical beam of a radar such that the wavelength of the acoustic signal matches the half-wavelength of the radar. As the frequency of the acoustic signal is varied, strongly enhanced scattering of the radar signal occurs when the Bragg match takes place. When this occurs, the Doppler shift of the radar signal produced by the Bragg scattering can be determined, as well as the atmospheric vertical velocity. Thus, the speed of sound as a function of altitude can be measured, from which virtual temperature (T_v) profiles can be calculated with appropriate corrections for vertical air motion. The virtual temperature of an air parcel is the temperature that dry air would have if its pressure and density were equal to those of a sample of moist air. As a rule of thumb, an atmospheric vertical velocity of 1 ms^{-1} can alter a T_v observation by 1.6°C.

RASS can be added to a radar wind profiler or to a sodar system. In the former case, the necessary acoustic subsystems must be added to the radar wind profiler to generate the sound signals and to perform signal processing. When RASS is added to a radar profiler, three or four

vertically pointing acoustic sources (equivalent to high quality stereo loud speakers) are placed around the radar wind profiler's antenna, and electronic subsystems are added that include the acoustic power amplifier and the signal generating circuit boards. The acoustic sources are used only to transmit sound into the vertical beam of the radar, and are usually encased in noise suppression enclosures to minimize nuisance effects that may bother nearby neighbors or others in the vicinity of the instrument.

When RASS is added to a sodar, the necessary radar subsystems are added to transmit and receive the radar signals and to process the radar reflectivity information. Since the wind data are obtained by the sodar, the radar only needs to sample along the vertical axis. The sodar transducers are used to transmit the acoustic signals that produce the Bragg scattering of the radar signals, which allows the speed of sound to be measured by the radar.

The vertical resolution of RASS data is determined by the pulse length(s) used by the radar. RASS sampling is usually performed with a 60- to 100-m pulse length. Because of atmospheric attenuation of the acoustic signals at the RASS frequencies used by boundary layer radar wind profilers, the altitude range that can be sampled is usually 0.1 to 1.5 km, depending on atmospheric conditions (e.g., high wind velocities tend to limit RASS altitude coverage to a few hundred meters because the acoustic signals are blown out of the radar beam).

9.2 Performance Characteristics

The following references provide documentation of performance characteristics for the upper-air measurement platforms covered in this guidance (lidar is included for completeness):

- Rawinsonde **[9] [75] [76] [77] [78] [79] [80] [81]**
- Sodar **[82] [83] [84] [85] [86] [87] [88]**
- Radar wind profiler **[89] [90] [91] [92]**
- RASS **[93] [94] [95] [96]**
- Lidar **[83] [97] [98] [99]**

9.2.1 Definition of Performance Specifications

Accuracy is defined as the degree of agreement of a measurement with an accepted reference or true value **[2]**. Determining the absolute accuracy of an upper-air instrument through an inter-comparison study is difficult because there is no “reference” instrument that can provide a known or true value of the atmospheric conditions. This is due in part to system uncertainties and inherent uncertainties caused by meteorological variability, spatial and temporal separation of the measurements, external and internal interference, and random noise. The only absolute accuracy check that can be performed is on the system electronics, by processing a simulated signal. Similarly, a true precision, or the standard deviation of a series of measured values about a mean measured reference value, can only be calculated using the system responses to repeated inputs of the same simulated signal.

The performance specifications provided by manufacturers for accuracy, precision, and other data quality objectives are derived in a number of ways, and it is prudent to understand the basis behind the published specifications. Manufacturers' specifications may be derived from the results of inter-comparison studies, from what the instrument system can resolve through the system electronics and processing algorithms, or a combination of these methods. It may not be practical for a user to verify the exact specifications claimed by the manufacturers. What is needed, however, is a means of verifying that the data obtained from an upper-air system compare reasonably to observations obtained from another measurement system. Guidance for system acceptance testing, field testing, auditing, and data comparison is provided in Section 9.6.

To quantify the reasonableness of the data, one compares observations from the upper-air system being evaluated to data provided by another sensor that is known to be operating properly. In assessing how well the sensors compare, two measures are commonly used. The first involves calculating the "systematic difference" between the observed variables measured by the two methods. The second involves calculating a measure of the uncertainty between the measurements, which is referred to as the "operational comparability" (or simply "comparability"), as described in reference **[100]**. Comparability, for these purposes, is the root-mean-square (rms) of a series of differences between two instruments measuring nearly the same population. The comparability statistic provides a combined measure of both precision and bias, and will express how well the two systems agree.

Using the ASTM notation **[100]**, the systematic difference (or bias) is defined as:

$$d = \frac{1}{n}\sum (x_{a,i} - x_{b,i}) \qquad \textbf{(9-1)}$$

where

n	=	number of observations
$x_{a,i}$	=	ith observation of the sensor being evaluated
$x_{b,i}$	=	ith observation of the "reference" instrument

Operational comparability (or root-mean-square error) is defined as

$$c = \sqrt{\frac{1}{n}\sum (x_{a,i} - x_{b,i})^2} \qquad \textbf{(9-2)}$$

Many of the inter-comparison programs discussed in the next section have evaluated instrument performance using the systematic difference and comparability statistics described

here. Other statistical measures that can be used include, for example, correlation coefficients and linear regression.

Another important performance specification for upper-air instrument systems is data recovery rate. Data recovery is usually calculated as the ratio of the number of observations actually reported at a sampling height to the total number of observations that could have been reported so long as the instrument was operating (i.e., downtime is usually not included in data recovery statistics but is treated separately). Data recovery is usually expressed as percent as a function of altitude. Altitude coverage for upper-air data is often characterized in terms of the height up to which data are reported 80 percent of the time, 50 percent of the time, etc.

9.2.2 Performance Characteristics of Radiosonde Sounding Systems

Radiosonde sounding systems are the most widely used upper-air instruments. The wind and thermodynamic data provided by these systems are critical to the numerical weather prediction (NWP) and forecasting programs conducted by all countries that provide such services. Thus, the performance characteristics of radiosondes and the relative accuracy of radiosonde winds have been the subject of a great deal of scrutiny over the last few decades. The World Meteorological Organization (WMO) and national weather agencies such as the U.S. NWS and British Meteorological Office have all sanctioned a number of inter-comparison studies to determine the performance characteristics of radiosonde systems (references **[9]**, **[75]**, and **[77]**). Inter-comparison and performance evaluation studies have also been conducted by independent researchers who have been interested in determining the accuracy of radiosonde wind and/or thermodynamic measurements for meeting specific research objectives (see reference**[81]** for a recent summary of some of these studies, especially those related to boundary-layer measurements). Some references are also provided in Table 9-4. Radiosonde systems will continue to be an important source of upper-air data for the foreseeable future, and efforts to characterize and improve radiosonde sounding system performance specifications continues **[79]**.

Performance tests of radiosonde systems have involved “flying” multiple radiosondes on the same balloon, and/or obtaining independent tracking information using high-precision tracking radars **[79]**. Such tests do not provide information on absolute accuracy of either the radiosondes or the tracking systems. Rather, they provide measures of the relative differences between comparable instrument systems, e.g., of temperature or relative humidity measured by different radiosondes flown at the same time and winds measured by radio theodolites or NAVAID systems. The NWS and WMO perform such tests to quantify the functional precision of the instruments, which is defined as the rms of the differences between the measurements, that is, if the differences have a Gaussian distribution then 67 percent of the differences would lie within the range specified by the functional precision. The functional precision is thus similar to the comparability statistic defined by Equation 9-2. Performance specifications for radiosonde systems are summarized in Table 9-1, the performance specifications are based on manufacturer's specifications and inter-comparison tests described in references **[77]** and **[79]**.

Errors and uncertainties encountered in radiosonde measurements, particularly errors in temperature and moisture, can occur at higher altitudes (e.g., beginning in the upper-troposphere), and are caused by factors such as exposure to solar radiation, sensor heating, and time lag. Data collected at lower altitudes (e.g., below about 10 km) do not tend to display such errors. Likewise, the relative accuracy of upper-air winds measured by radiosondes tends to decrease with increasing altitude. This is due in part to many weather services using radio theodolite sounding systems, where errors in tracking angles (especially elevation) become more troublesome as the balloon approaches the horizon and the antenna reaches its tracking limit.

At altitudes below about 10 km, radiosonde winds tend to show good agreement with other independent upper-air measurements **[79]**. As noted earlier in this document, there are circumstances under which data resolution within the lowest few hundred meters can be compromised.

9.2.3 Performance Characteristics of Remote Sensing Systems

Many of the studies that have been performed to estimate the accuracy and precision of remote sensors were based on inter-comparisons to tower-based measurements. These comparisons have generally assumed that the tower measurements provide the known standard and are representative of the same environment measured by the remote sensors. However, differences between point measurements from *in situ* sensors located on the tower and volume-averaged measurements from the remote sensors located near the tower are expected to lead to differences in the results, even though conditions for these inter-comparisons are likely as close to "ideal" as one could expect. The performance of remote profiling instrumentation is greatly influenced by individual site characteristics, instrument condition, and operating parameters established for the equipment.

Table 9-1 includes estimates of expected performance characteristics for remote sensing systems that are installed and working properly. These results should be used for establishing data quality objectives for upper-air programs and as a basis for interpreting results from inter-comparison programs or performance audits of upper-air equipment (see Section 9.6). To avoid ambiguities in wind direction associated with light and variable winds, it is recommended that the wind direction comparability calculations be made only when actual wind speeds are greater than approximately 2 ms^{-1}.

9.3 Monitoring Objectives and Goals

When the primary use of upper-air data is for the analysis and modeling of meteorological and air quality conditions in the boundary layer and lower troposphere, the focus of the upper air program should be to maximize the temporal and spatial resolution of the data collected in this portion of the atmosphere, i.e. the first one to three km. Each modeling and analysis application will have its own unique objectives and scales of interest. However there are certain characteristics that have a large bearing on the type of upper-air measurement system chosen, the manner in which it is operated, and data processing and archival procedures. These

characteristics include the duration of the measurement program, that is whether the measurements are part of a long-term monitoring program of seasonal to yearly extent, or a shorter-term intensive field campaign characterized by a greater number of measurements. The types of measured and derived meteorological variables required for the modeling/analysis, including the required spatial and temporal resolution, will also affect the choice of measurement system, as will the need, in many cases, to make comparable measurements with surface-based meteorological systems.

The choice of upper-air measurement technologies is considerably greater now than at any time in the last two decades. With that choice comes the need to carefully consider the requirements of the application and to choose and configure the appropriate systems. Considerable field experience has been gained in the use of the various measurement technologies, especially since 1990. The following discussion for each class of upper-air measurement system is meant to stimulate thinking regarding the best match of the system to the specific application.

9.3.1 Data Quality Objectives

Inherent in any measurement program is the need to establish data quality objectives. These relate the quality of measurements obtained to the level of uncertainty that decision makers are willing to accept in the data and results derived from the data **[65]**. Data quality objectives state how "good" the data need to be to satisfy the program objectives. The stated objectives generally include completeness, systematic difference, and comparability. Operators of the instruments should let the data quality objectives be determined based on instrument performance specifications and modeling and analysis needs. Data quality objectives should be specified for all of the primary variables measured by the instrument.

To check whether or not the data meet the data quality objectives from an instrument performance perspective, a comparison to another sensor that is known to be operating properly is recommended (see Section 9.5). In assessing how well the sensors compare, the systematic difference and the operational comparability can be computed and compared to the data quality objectives that are presented in Table 9-4.

In evaluating the sodar and radar wind profiler data, the primary criteria for comparison are the component data; the vector wind speed and wind direction are secondary. The indicated values for u and v for the sodar and radar wind profiler in Table 9-4 refer to the components along the antenna axes, and for these instruments, the component comparisons should be performed using calculated values along the antenna axes. Values along the meteorological axes (north/south and east/west) should only be used if evaluating a radiosonde. For the sodar and radar wind profiler, the data quality objective for the vector wind speed and wind direction comparisons should be applied when winds are greater than 2 to 3 ms^{-1}. Note that the values presented in Table 9-5 are based on a number of studies and were reviewed by several measurement experts participating in an EPA-sponsored workshop on upper-air measurement systems.

Table 9-4.

Suggested data quality objectives for upper-air measurement systems.

Measurement Method	Systematic Difference	Comparability
Radiosonde	p:± 0.5 mb T: ± 0.2°C RH: ± 10% u,v: ± 0.5 to 1 ms^{-1}	P (as height):± 24 m T: ± 0.6°C T_d: ± 3.3°C WS: ± 3.1 ms^{-1} WD: ± 18° to ± 5°[a]
Sodar[b]	u,v: ± 1 ms^{-1} WS: ± 1 ms^{-1} WD: ± 10°	u,v: ± 2 ms^{-1} WS: ± 2 ms^{-1} WD: ± 30°
Radar wind profiler[b]	u,v: ± 1 ms^{-1} WS: ± 1 ms^{-1} WD: ± 10°	u,v: ± 2 ms^{-1} WS: ± 2 ms^{-1} WD: ± 30°
RASS	±1°C	±1.5°C

[a] Over a WS range from 3 to 21 ms^{-1}.

[b] For wind speeds greater than approximately 2 ms^{-1}.

Comparison results in excess of the data quality objectives do not necessarily mean that the data are invalid. In making this assessment, it is important to understand the reasons for the differences. Reasons may include unusual meteorological conditions, differences due to problems in one or both instruments, or differences due to sampling techniques and data reduction protocols. Both the reasons for and the magnitude of the differences, as well as the anticipated uses of the data, should be considered in determining whether the data quality objectives are met. This assessment should be part of the QA protocol.

Data completeness for radiosonde sounding systems is usually not significantly affected by outside environmental conditions such as high winds, precipitation, or atmospheric stability. However, environmental factors can have a significant effect on the rate of data capture for remote sensing systems.

9.4 Siting and Exposure

Siting and exposure issues related to radiosonde sounding systems, sodar, radar wind profiler, and RASS meteorological measurement systems are addressed in this section.

Careful planning should accompany the siting of upper-air measurement systems, since siting and exposure directly affect the quality of the data. The complexities of ground based remote sensing devices provide a challenge for the user to balance the conditions favorable for

the technology with the availability of sites and the overall data collection goals of the program. Site selection may benefit from the experience of vendors or users of the type of instrument to be installed. Additional information on siting can be found in reference **[2]**. Listed below are some key issues to consider in siting upper-air systems.

- **Representative location.** Sites should be located where upper-air data are needed to characterize the meteorological features important to meeting the program objectives. Panoramic photographs should be taken of the site to aid in the evaluation of the data and preparation of the monitoring plan. Data collected at sites in regions with local geographic features such as canyons, deep valleys, etc., may be unrepresentative of the surrounding area and should be avoided, unless such data are needed to resolve the local meteorological conditions. Measurements made in complex terrain may be representative of a much smaller geographical area than those made in simple homogeneous terrain. See reference **[101]** for a discussion of the influence of terrain on siting and exposure of meteorological instrumentation.

- **Site logistics.**
  - Adequate power should be available for the instrument system as well as an environmentally controlled shelter that houses system electronics, and data storage and communication devices.
  - The site should be in a safe, well lit, secure area with level terrain, sufficient drainage, and clear of obstacles. The site should allow adequate room for additional equipment that may be required for calibrations, audits, or supplementary measurements.
  - A fence should be installed around the equipment and shelter to provide security, and appropriate warning signs should be posted as needed to alert people to the presence of the equipment.
  - A remote data communications link (e.g., dedicated leased line, standard dial-up modem line, or a cellular telephone link) should be installed at the monitoring site. It is recommended that a 9600 baud or higher line be established to facilitate rapid data transfer and uploading and downloading of information. A site in a remote location with no communication capabilities may collect valid data, but if the system goes down it may not be discovered until the next time the site is visited.

- **Collocation with surface meteorological measurements.** Several advantages can be gained by locating an upper-air site with or near an existing meteorological monitoring station. For instance, collocated data can be used for data validation purposes and for performing reasonableness checks (e.g., do surface winds roughly agree with near-surface upper-air winds, surface temperatures with near-surface RASS measurements). Existing shelter, power, and personnel could also be used for operating the upper-air instrument. Additional surface meteorological measurements of wind speed, wind direction, temperature and humidity are recommended. The height of the wind sensors will depend on the terrain. In homogeneous terrain, wind data collected at a height of 10 m may be sufficient.

- **Instrument noise.** Sodar and RASS generate noise that can disturb nearby neighbors. Depending on the type of sodar or RASS instrument, power level, frequency, acoustic shielding around the system, and atmospheric conditions, the transmitted pulse can be heard from tens of meters up to a kilometer away. An optimum site is one that is isolated from acoustically sensitive receptors **[102]**.
- **Passive interference/noise sources**. Objects such as stands of trees, buildings or tall stacks, power lines, towers, guy wires, vehicles, birds, or aircraft can reflect sodar or radar transmit pulses and contaminate the data. Not all sites can be free of such objects, but an optimum site should be selected to minimize the effects of such obstacles. If potential reflective "targets" are present at an otherwise acceptable site, the beams of the instrument should be aimed away from the reflective objects. In the case of sodars, locating the antennas so that there are no direct reflections from objects will help minimize potential contamination. In the case of the radar profiler, it is best to aim the antennas away from the object and orient a phased array antenna's corners so they are pointing toward the objects. As a rule of thumb, sites with numerous objects taller than about 15° above the horizon should be avoided. The manufacturers of the remote sensing equipment should be contacted regarding software that may be available to identify and minimize the effects of these passive noise sources.
- **Active interference/noise sources.** For sodars, noise sources such as air conditioners, roadways, industrial facilities, animals, and insects will degrade the performance of sodar systems **[102]**. If proximity to such sources cannot be avoided, then additional acoustic shielding may help minimize the potentially adverse effects on the data. In general, noise levels below 50 decibels (dBA) are considered to be representative of a quiet site, while levels above 60 dBA are characteristic of a noisy site. For radar wind profilers and RASS, radio frequency (RF) sources such as radio communications equipment and cellular telephones may have an adverse effect on performance.
- **Licenses and Ordinances**. Before operating a remote sensor it is recommended that all applicable requirements for operation of equipment be addressed. For example, to operate a radar wind profiler or a RASS, a Federal Communications Commission (FCC) license is required. For radiosonde sounding systems (or other balloon-borne systems), a Federal Aviation Administration (FAA) waiver may be required. Local noise ordinances may limit the operation of sodar or RASS instruments. Some of these requirements may take several months to address and complete.
- **Surveying Candidate Locations.** Prior to final site selection, a survey is recommended to identify audio sources **[103]** and RF sources that may degrade system performance. Additionally, panoramic photographs should be taken to aid in the evaluation of the candidate site and for the preparation of the monitoring plan. As part of the survey, appropriate topographic and other maps should be used to identify other potential sources of interference, such as roadways and airports.

9.5 Installation and Acceptance Testing

This section provides guidance for the installation and acceptance testing of upper-air monitoring systems; similar guidance for in situ sensors is provided in Section 8.2.

The installation period is the optimal time to receive appropriate training in instrument principles, operations, maintenance, and troubleshooting, as well as data interpretation and validation. Meteorological consultants as well as some manufacturers and vendors of meteorological instruments provide these services.

Installation procedures specific to upper-air monitoring systems include the following:

- The latitude, longitude, and elevation of the site should be determined using U.S. Geological Survey (USGS) topographical maps, other detailed maps, or a GPS instrument.
- The orientation of antennas of the sodar, radar profiler, or radio theodolite systems should be defined with respect to true north. One recommended method is to use the solar siting technique **[2]** . This technique enables determination of true north at any location using a compass (or other pointing device suitable for measuring the azimuth angle to the sun), a computer program, the site latitude and longitude, and accurate local time.
- The site should be documented as follows:
    - Photographs in sufficient increments to create a documented 360° panorama around the antennas should be taken. Additionally, pictures of the antenna installation, shelter and any obstacles that could influence the data should be obtained.
    - Photographs of the instrument, site, shelter, and equipment and computers inside the shelter should be obtained.
    - A detailed site layout diagram that identifies true north and includes the locations of the instrument, shelter, other equipment, etc. should be prepared. An example of such a diagram is shown in Figure 9-4. Additionally, it is recommended that the site layout diagram include the electrical and signal cable layout, and the beam directions of any remote sensor.
    - A vista table that documents the surroundings of the site in 30° increments should be prepared. Vistas for the beam directions, if they are not represented by the 30° views (±5°), should be included. The table should identify any potential passive and active noise sources in each direction, and the approximate distance and elevation angle above the horizon to the objects. An example is shown in Table 9-5.

An acceptance test is used to determine if an instrument performs according to the manufacturer's specifications **[2]**. Manufacturer's procedures for unpacking, inspection, installation, and system diagnostics should be followed to assure that all components are functioning appropriately. All acceptance-testing activities should be documented in the station log.

Once the system is installed, a final field check is needed to assure that the data are reasonable. This is best performed using collocated meteorological information from towers or other upper-air sensors. In the absence of these data sources, nearby upper-air data from the NWS radiosonde network, the NOAA profiler network, aircraft reports, National Center for Environmental Prediction (NCEP) high resolution mesoscale analyses, or other upper-air data can be used. It is important to have an individual trained in the interpretation of the data perform a thorough review of at least several days of data. This check is not meant to evaluate whether or

not the data meet the manufacturer's data specifications, but is intended to identify problems such as:

- Component failures
- Incorrect or improper operating/sampling parameters
- Antenna azimuth angles specified improperly or incorrectly measured
- Siting problems (active and passive interfering noise sources)

Shortly after the installation and startup of an instrument, a system and performance audit should be performed. These audits will provide information for the qualitative and quantitative assessment of the performance of the system, as well as the adequacy of the standard operating procedures used for collection, processing, and validation of the data. To best assure that the data collected is of known quality, and that potential problems are identified early, it is recommended the initial audit be performed within 30 days of the start-up date.

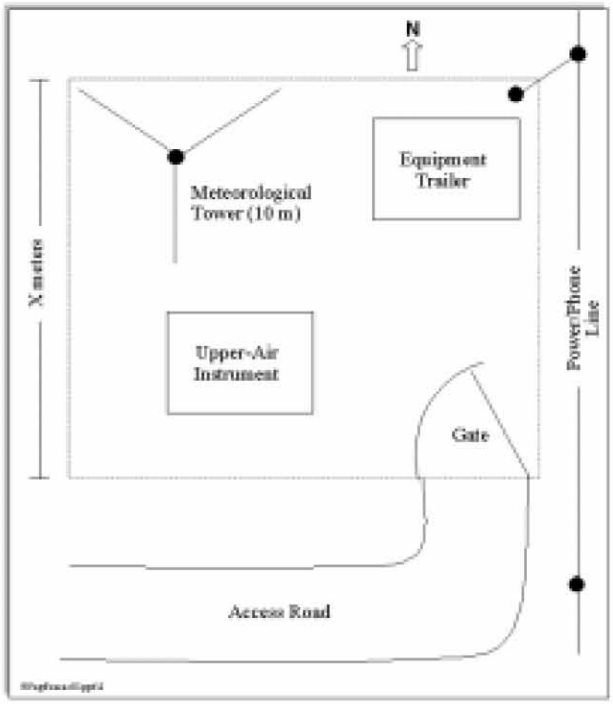

Figure 9-4 Example site layout diagram.

9.6 Quality Assurance and Quality Control

This section provides information on QAQC procedures unique to upper-air measurement systems. Generic material on QAQC procedures for meteorological systems and definitions of terms used in QAQC is presented in Section 8.

With some exceptions (e.g., rawinsonde measurements of pressure, temperature, and humidity) upper-air monitoring systems provide indirect measurements of the meteorological variables used in dispersion modeling. This presents a unique challenge to the quality assurance and quality control (QAQC) of these systems; for example, there is no upper-air counterpart to the bench top calibration of a wind vane. The alternative to the bench-top calibration is a calibration using a collocated transfer standard; this involves locating an identical instrument as close as practical to the instrument being calibrated (see Section 8.3) - again, as with the bench-top procedure, there is no upper-air counterpart to the collocated transfer standard for a wind vane. Similarly, there is no upper-air counter part to the performance audit of a wind vane (as explained in Section 8, calibrations and audits are one and the same as far as "what" takes place; the difference has to do with the independence of the person conducting the audit). Given the inability to conduct a true performance audit, the onus for claims of data validity for most upper-air measurements falls on the systems audit - this, as explained in Section 8.4, is essentially a challenge to the QAPP and provides an overall assessment of the commitment to data validity.

Alternative procedures for calibrations and performance audits of upper-air measurement systems are based on inter-comparisons with other measurement systems - these alternatives are discussed in Sections 9.6.1 (Calibration Methods) and 9.6.2 (Systems and Performance Audits).

Before discussing quality assurance programs, it is useful to explain the difference between quality control (QC) and quality assurance (QA). For the purposes of this document, QC refers to the operational procedures used to ensure that a measurement process is working properly. QC procedures include periodic instrument calibrations, site checks, data examination for reasonableness, and data validation. QC procedures produce quantitative documentation upon which claims of accuracy can be based. QA refers to all the planned or systematic actions necessary to provide adequate confidence that the entire measurement process is producing data that meets the data quality objectives established for a monitoring program. These actions include routine evaluation of how the QC procedures are implemented (system audits) and assessments of instrument performance (performance audits). Summarized below are details on the preparation of a Quality Assurance Project Plan (QAPP) and key elements that are unique to upper-air measurement methods.

Table 9-5

Example site vista table

VISTA, ORIENTATION, AND LEVEL AUDIT RECORD			
Date:	January 3, 1996	Site Name:	Site 5
Key Person:	John Sitetech	Project:	ABC
Instrument:	Radar Wind Profiler	Latitude:	31°10'25"
Model Number:	GEN-1500	Longitude:	91°15'33"
Serial Number:	1234	Elevation:	172 m
Software version:	3.95		
Rotation angle		Direction	
System:	147°true	Beam 1:	146°
Measured:	146°true	Beam 2:	236°
Difference:	1°		
		Firing order:	W, beam 1, beam 2
Array Level:	< 0.5°	Declination:	11° east (solar verification)
Azimuth Angle (deg.)			
Magnetic	True	Terrain Elevation Angle (deg.)	Features/Distance
--	0	12	Buildings and power lines at ~ 300 m.
--	30	19	Stack at 150-200 m.
--	60	22	Power pole at 10 m, < 5° beyond.
--	90	4	Low trees and bushes at 10 m.
--	120	15	Power lines at 200-300 m
--	150	4	Trees at 30-40 m.
----	180	0	Looking out over the lake.
--	240	< 2	Looking out over the lake, can see land.
--	270	< 2	Looking out over the lake, can see land.
--	300	3	Trees and telephone pole at 100 m.
--	330	14	Light pole at 25 m. Buildings at ~250 m.

9.6.1 Calibration Methods

A calibration involves measuring the conformance to or discrepancy from a specification for an instrument and an adjustment of the instrument to conform to the specification. In this sense, other than directional alignment checks, a true calibration of the upper-air instruments described in this document is difficult. Due to differences in measurement techniques and sources of meteorological variability, direct comparison with data from other measurement platforms is not adequate for a calibration. Instead, a calibration of these sensors consists of test signals and diagnostic checks that are used to verify that the electronics and individual components of a system are working properly. Results from these calibrations should not be used to adjust any data. All calibrations should be documented in the station log.

System calibration and diagnostic checks be performed at six month intervals, or in accordance with the manufacturer's recommendations, whichever is more frequent. The alignment of remote sensing antennas, referenced to true north, should be verified at six month intervals. Generic guidance and definitions of terms related to calibrations is provided in Section 8.3.

Radiosonde Sounding Systems For radiosonde sounding systems, the primary calibration that is required is to obtain an accurate surface pressure reading using a barometer that is regularly calibrated and periodically audited. This pressure reading is used to determine if an offset needs to be applied to the radiosonde pressure data. If an offset is needed, the data systems of the commercially available instruments will make the adjustment automatically. It is also useful to obtain surface readings of temperature and atmospheric moisture using a psychrometer or similar instrument. These data can be used to provide a reality check on the radiosonde measurements. This check can be performed using data from a nearby tower. A more robust check can be made by placing the sonde in a ventilated chamber and taking readings that are then compared to temperature and moisture measurements made in the chamber using independent sensors. The alignment of the theodolite should be validated against the reference marker that was installed at the time of system setup.

Sodar Recent advances in instrumentation for auditing of sodar instruments **[104]** have led to the development of a transponder that can simulate a variety of acoustic Doppler shifted signals on certain sodars. This instrument can be used to verify the calibration of the sodar's total system electronics and, in turn, validate the overall system operation in terms of wind speed and altitude calculations. However, such a check should not be considered a “true” calibration of the system since it does not consider other factors that can affect data recovery. These factors include the system signal-to-noise ratio, receiver amplification levels, antenna speaker element performance, beam steering and beam forming for phased-array systems, and overall system electronic noise.

Radar Wind Profilers and RASS A transponding system for radar does not yet exist, but the feasibility of such a system is being explored. Therefore, there is no simple means at present of verifying the accuracy of the Doppler shifted signals in the field other than to perform a comparison with some other measurement system, as described later in this section. Instead, calibrations of radar wind profiler and RASS systems are performed and checked at the system component level. These checks should be performed in accordance with the manufacturer's

recommendations. Like some sodar systems, the radar systems use both software and hardware diagnostics to check the system components.

9.6.2 System and Performance Audits

Audits of upper-air instrumentation to verify their proper operation pose some interesting challenges. While system audits can be performed using traditional system checks and alignment and orientation techniques, performance audits of some instruments require unique, and sometimes expensive procedures. In particular, unlike surface meteorological instrumentation, the upper-air systems cannot be challenged using known inputs such as rates of rotation, orientation directions, or temperature baths. Recommended techniques for both system and performance audits of the upper-air instruments are described below. These techniques have been categorized into system audit checks and performance audit procedures for radiosonde sounding systems, radar wind profilers, sodars, and RASS.

9.6.2.1 Systems Audit

System audits of an upper-air station should include a complete review of the QAPP, any monitoring plan for the station, and the station's standard operating procedures. The system audit will determine if the procedures identified in these plans are followed during station operation. Deviations from the plans should be noted and an assessment made as to what effect the deviation may have on data quality. To ensure consistency in the system audits, a checklist should be used. System audits should be conducted at the beginning of the monitoring program and annually thereafter.

Radiosonde Sounding Systems For radiosonde sounding systems, an entire launch cycle should be observed to ensure that the site technician is following the appropriate procedures. The cycle begins with the arrival of the operator at the site and ends with completion of the sounding and securing of the station. The following items should be checked:

- Ground station initialization procedures should be reviewed to ensure proper setup.
- Sonde initialization procedures should be reviewed to verify that the sonde has been properly calibrated.
- Balloon inflation should be checked to ensure an appropriate ascent rate.
- Proper and secure attachment of sonde to balloon should be verified.
- Orientation of the radio theodolite antenna should be checked, using solar sitings when possible. The antenna alignment should be maintained within ±2°.
- The vertical angle of the radio theodolite antenna should be checked and should be within ±0.5°.
- Data acquisition procedures should be reviewed and a sample of the acquired data should be inspected.
- Data archiving and backup procedures should be reviewed.

- Flight termination and system shutdown procedures should be reviewed.
- Preventive maintenance procedures should be reviewed and their implementation should be checked.
- Data processing and validation procedures should be reviewed to ensure that questionable data are appropriately flagged and that processing algorithms do not excessively smooth the data.
- Data from several representative launches should be reviewed for reasonableness and consistency.
- Station logbooks, checklists, and calibration forms should be reviewed for completeness and content to assure that the entries are commensurate with the expectations in the procedures for the site.

Remote Sensing Instrumentation

A routine check of the monitoring station should be performed to ensure that the local technician is following all standard operating procedures (SOPs). In addition, the following items should be checked:

- The antenna and controller interface cables should be inspected for proper connection. If multi-axis antennas are used, this includes checking for the proper connection between the controller and individual antennas.
- Orientation checks should be performed on the individual antennas, or phased-array antenna. The checks should be verified using solar sitings when possible. The measured orientation of the antennas should be compared with the system software settings. The antenna alignment should be maintained within ±2°.
- For multi-axis antennas, the inclination angle, or zenith angle from the vertical, should be verified against the software settings and the manufacturer's recommendations. The measured zenith angle should be within ±0.5° of the software setting in the data system.
- For phased-array antennas, the array should be level within ±0.5° of the horizontal.
- For multi-axis sodar systems, a separate distinct pulse, or pulse train in the case of frequency-coded pulse systems, should be heard from each of the antennas. In a frequency-coded pulse system there may be a sound pattern that can be verified. The instrument manual should be referenced to determined whether there is such a pattern.
- For sodar systems, general noise levels should be measured, in dBA, to assess the ambient conditions and their potential influence on the performance of the sodar.
- The vista table for the site (see Section 9.5) should be reviewed. If a table is not available then one should be prepared.
- The electronic systems and data acquisition software should be checked to ensure that the instruments are operating in the proper mode and that the data being collected are those specified by the SOPs.

- Station logbooks, checklists, and calibration forms should be reviewed for completeness and content to assure that the entries are commensurate with the expectations in the procedures for the site.
- The site operator should be interviewed to determine his/her knowledge of system operation, maintenance, and proficiency in the performance of quality control checks.
- The antenna enclosures should be inspected for structural integrity that may cause failures as well as for any signs of debris that may cause drainage problems in the event of rain or snow.
- Preventive maintenance procedures should be reviewed for adequacy and implementation.
- The time clocks on the data acquisition systems should be checked and compared to a standard of ±2 minutes.
- The data processing procedures and the methods for processing the data from sub-hourly to hourly intervals should be reviewed for appropriateness.
- Data collected over a multi-day period (e.g., 2-3 days) should be reviewed for reasonableness and consistency. The review should include vertical consistency within given profiles and temporal consistency from period to period. For radar wind profilers and sodar, special attention should be given to the possibility of contamination of the data by passive or active noise sources.

9.6.2.2 Performance Audit and Comparison Procedures

Performance audits should be conducted at the beginning of the monitoring program and annually thereafter. A final audit should be conducted at the conclusion of the monitoring program. An overview of the recommended procedures for performance auditing is provided below.

Radiosondes Performance auditing of radiosonde sounding systems presents a unique challenge in that the instrument is used only once and is rarely recovered. Therefore, a performance audit of a single sonde provides little value in assessing overall system performance. The recommended approach is to audit only the instruments that are used to provide ground truth data for the radiosondes prior to launch (thermometer, relative humidity sensor, psychrometer, barometer, etc.). The reference instruments used to audit the site instruments should be traceable to a known standard. Details on these audit methods can be found in reference **[2]**.

In addition, a qualitative assessment of the direction and speed of balloon travel should be made during an observed launch for comparison with the computed wind measurements. An alternative approach is to attach a second sonde package to the balloon, track it from an independent ground station, and compare the results of the two systems. An optical tracking system is adequate for this type of comparison.

Remote Sensing Instrumentation Methods for performance audits and data comparisons of remote sensing instrumentation have been under development for a number of years. Only recently has interim guidance reference **[2]** been released to help standardize performance audit methods. Even with the release of that guidance, there are still a number of areas undergoing

development. Recommended procedures for performance audits and data comparisons of remote sensors which are presented below typically incorporate inter-comparison checks. If inter-comparison checks are used, a quick review of the datasets should be performed before dismantling the comparison system.

Sodar. The performance audit is used to establish confidence in the ability of the sodar to accurately measure winds. A performance audit of a system typically introduces a known value into the sensor and evaluates the sensor response. It may not be possible to perform this type of audit for all types of sodar instruments. In this case, a comparison between the sodar and another measurement system of known accuracy should be performed to establish the reasonableness of the sodar data. With any of the audit or comparison methods, the evaluation of the data should be performed on a component specific basis that corresponds to the sodar beam directions. Any of the following approaches may be considered in the sodar performance evaluation.

- Comparison with data from an adjacent tall tower. Using this approach, conventional surface meteorological measurements from sensors mounted on tall towers (at elevations within the operating range of the sodar) are compared with the sodar data. This method should only be used if the tall tower is an existing part of a monitoring program and its measurements are valid and representative of the sodar location. At least 24 hours of data should be compared. The tower data should be time averaged to correspond to the sodar averaging interval and the comparisons should be made on a component basis. This comparison will provide an overall evaluation of the sodar performance as well as a means for detecting potential active and passive noise sources.
- Comparison with data from another sodar. This comparison uses two sodars operating on different frequencies. The comparison sodar should be located in an area that will allow it to collect data that is representative of the site sodar measurements. At least 24 hours of data should be collected for the comparison. If the measurement levels of the two sodars differ, the comparison sodar data should be volume averaged to correspond with the site sodar. Additionally, the comparison sodar time averaging should correspond to the site sodar. As with the adjacent tall tower, the comparison should be performed on a component basis. This comparison will provide an overall evaluation of the sodar performance as well as a means for detecting potential active and passive noise sources.
- Comparison with radiosonde data. This comparison uses data obtained from a radiosonde carried aloft by a free-flight, slow-rise balloon. The balloon should be inflated so the ascent rate is about 2 ms^{-1}. This will provide the appropriate resolution for the comparison data, within the boundary layer. The wind data should be volume averaged to correspond with the sodar data and the comparisons should be made on a component as well as a total vector basis. The launch times should be selected to avoid periods of changing meteorological conditions. For example, evaluation of the comparison data should recognize the potential differences due to differences in both the spatial and temporal resolution of the measurements (i.e., the instantaneous data collected by the radiosonde as compared with the time averaged data collected by the sodar). This comparison will provide an overall evaluation of the sodar performance as well as a means for detecting potential active and passive noise sources.
- Comparison with tethersonde data. The tethersonde comparison is performed using single or multi-sonde systems. Using this approach, a tethered balloon is used to lift the

sonde(s) to altitude(s) corresponding with the sodar measurement levels. This method should collect data at one or more layers appropriate to the program objectives. At a minimum, data corresponding to the equivalent of five sodar averaging periods should be collected at each altitude. Multiple altitudes can be collected simultaneously using a multi-sonde system with two or more sondes. The individual sonde readings should be processed into components that correspond to the sodar beam directions and then time averaged to correspond to the sodar averaging period. This comparison will provide an overall evaluation of the sodar performance as well as a means for detecting potential active and passive noise sources.

- Comparison with data from an anemometer kite. This measurement system is suitable in relatively high wind speed conditions that would preclude the use of a tethersonde. The kite anemometer consists of a small sled type kite attached to a calibrated spring gauge. Horizontal wind speeds are determined from the pull of the kite on the spring gauge. The altitude of the kite (i.e. the height of the measured wind) is determined from the elevation angle and the distance to the kite. The wind direction is determined by measuring the azimuth angle to the kite. At a minimum, data corresponding to the equivalent of five sodar averaging periods should be collected at a level appropriate to the monitoring program objectives. The wind speed and kite azimuth and elevation readings should be taken every minute. The individual readings should be processed into components that correspond to the sodar beam directions and then time averaged to correspond to the sodar averaging period. This comparison will provide an overall evaluation of the sodar performance as well as a means for detecting potential active and passive noise sources.
- Use of a pulse transponding system. A pulse transponding system provides a means of testing the sodar system processing electronics for accuracy through the interpretation of simulated Doppler shifted signals at known time intervals **[104]**. This method can be considered an audit rather than a comparison because it provides a signal input equivalent to a known wind speed, wind direction and altitude to test the response of a sodar system. At least three averaging periods of transponder data should be collected with the sodar in its normal operating mode. Depending on the sodar configuration, this method along with an evaluation of the internal consistency of the sodar data to identify potential passive and active noise sources, may serve as the performance audit without the need of further comparisons. In the case of phased array sodars, an additional comparison is needed to verify proper beam steering. This comparison may be performed using any of the methods above. For this check, three sodar averaging periods at a single level are sufficient. It should be noted that current transponder technology is limited to sodars with three beams.

Radar Wind Profilers. At present, the performance of radar wind profilers can only be evaluated by comparison to collocated or nearby upper-air measurements. Various types of comparison instruments can be used including tall towers, sodar, radiosonde sounding systems, and tethersondes. A tethersonde may be used, but care should be taken to ensure that it does not interfere with the radar operation. Since it is important to have confidence in the reference instrument, an independent verification of operation of the reference instrument should also be obtained. If using a sodar or a radiosonde sounding system, the procedures outlined above should be followed to ensure acceptable operation of the system. If data from an adjacent tower are used, then it is recommended that the quality of the tower-based data be established. The

comparison methods should follow those described for sodars above. Where RASS acoustic sources may interfere with the comparison sodar operation, care should be taken to identify potentially contaminated data.

RASS. Like the radar wind profiler, the evaluation of a RASS relies on a comparison to a reference instrument. The recommended method is to use a radiosonde sounding system to measure the variables needed to calculate virtual temperature (i.e., pressure, temperature, and humidity). Sufficient soundings should be made for comparisons during different times of the day to evaluate the performance of the system under different meteorological conditions. Data collected from the sonde should be volume averaged into intervals consistent with the RASS averaging volumes, and the values should be compared on a level-by-level and overall basis.

9.6.3 Standard Operating Procedures

Standard operating procedures (SOPs) should be developed that are specific to the operations at a given site. The purpose of an SOP is to spell out operating and QC procedures with the ultimate goal of maximizing data quality and data capture rates. Operations should be performed according to a set of well defined, written SOPs with all actions documented in logs and on prepared forms. SOPs should be written in such a way that if problems are encountered, instructions are provided on actions to be taken. At a minimum, SOPs should address the following issues:

- Installation, setup, and checkout
- Site operations and calibrations
- Operational checks and preventive maintenance
- Data collection protocols
- Data validation steps
- Data archiving

9.6.4 Operational Checks and Preventive Maintenance

Like all monitoring equipment, upper-air instruments require various operational checks and routine preventive maintenance. The instrument maintenance manuals should be consulted to determine which checks to perform and their recommended frequency. The quality and quantity of data obtained will be directly proportional to the care taken in ensuring that the system is routinely and adequately maintained. The site technicians who will perform preventive and emergency maintenance should be identified. The site technicians serve a crucial role in producing high quality data and thus should receive sufficient training and instruction on how to maintain the equipment. Some general issues related to operational checks and preventive maintenance should be addressed in the QAPP, including:

- Identification of the components to be checked and replaced
- Development of procedures and checklists to conduct preventive maintenance
- Establishment of a schedule for checks and preventive maintenance

- Identification of persons (and alternates) who will perform the checks and maintenance
- Development of procedures for maintaining spare components that need frequent replacement

Listed below are some key items to be included in the operational checklists for each of the different types of instrumentation. The list is by no means complete, but should serve as a starting point for developing a more thorough set of instrumentation checks.

- Safety equipment (first aid kit, fire extinguisher) should be inventoried and checked.
- After severe or inclement weather, the site should be visited and the shelter and equipment should be inspected.
- Computers should be routinely monitored to assure adequate disk space is available, and diagnosed to ensure integrity of the disk.
- A visual inspection of the site, shelter, instrument and its components should be made.
- Data should be backed up on a routine basis.
- If the remote sensors are operated during the winter, procedures for snow and ice removal should be developed and implemented, as needed.
- The clock time of the instruments should be monitored, and a schedule for updating the clocks established based on the timekeeping ability of the instrument.
- The antenna level and orientation of sodar, radar, RASS, and radio theodolite radiosonde systems should be verified periodically.
- The inside of the antennas/enclosures of the sodar, radar and RASS systems should be inspected and any leaves, dust, animals, insects, snow, ice, or other materials removed. Since the antennas are open to precipitation, drain holes are provided to allow water to pass through the bottom of the antennas. These holes should be periodically inspected and cleaned.
- Cables and guy wires securing the equipment should be checked to ensure that they are tight and in good condition.
- Antenna cables and connections should be inspected for signs of damage due to normal wear, moisture, or animal activities.
- For sodar systems, the site technician(s) should listen to assure that the system is transmitting on all axes and in the correct firing sequence. For three-axis systems, this is accomplished by listening to each antenna. For phased-array systems, this can be accomplished by standing away from the antenna in the direction of each beam and listening for relatively stronger pulses.
- The integrity of any acoustic enclosures and acoustic-absorbing materials should be inspected. Weathering of these items will degrade the acoustic sealing properties of the enclosure and reduce the performance.
- For a radar profiler with RASS, acoustic levels from the sound sources should be measured using a sound meter (ear protection is required) and readings should be compared with manufacturer's guidelines.

All operational checks and preventive maintenance activities should be recorded in logs and/or on appropriate checklists, (electronic and/or paper) which will become part of the documentation that describes and defends the overall quality of the data produced.

9.6.5 Corrective Action and Reporting

A corrective action program must have the capability to discern errors or defects at any point in an upper-air monitoring program. It is an essential management tool for coordination, QC, and QA activities. A workable corrective action program must enable identification of problems, and establish procedures for reporting problems to the responsible parties, tracing the problems to the source, planning and implementing measures to correct the problems, maintaining documentation of the results of the corrective process, and resolution of each problem. The overall documentation associated with the corrective action and reporting process will become part of the documentation that describes and defends the overall quality of the data produced. A sample correction form can be found in reference **[65]**.

9.6.6 Common Problems Encountered in Upper-Air Data Collection

Studies performed to date have indicated that the upper-air measurement systems described in this document can reliably and routinely provide high quality meteorological data. However, these are complicated systems, and like all such systems are subject to sources of interference and other problems that can affect data quality. Users should read the instrument manuals to obtain an understanding of potential shortcomings and limitations of these instruments. If any persistent or recurring problems are experienced, the manufacturer or someone knowledgeable about instrument operations should be consulted.

Radiosonde data are susceptible to several problems, including the following:

- **Poor ventilation.** Prior to launch, lack of ventilation of the sonde may result in unrepresentative readings of temperature and relative humidity (and thus dew-point temperature) at or near the surface.
- **Radio frequency (RF) interference.** RF interference may occasionally produce erroneous temperature, dew-point temperature, and relative humidity measurements, which appear as spikes in the data when plotted in a time series or profile plot.
- **Uncertainties in the tracking mechanism.** Uncertainties in a radio theodolite's tracking mechanism may produce unrealistic changes in the wind speed and direction, especially when the antenna's elevation angle is less than about 10°.
- **Tracking problems.** Tracking of radiosondes can be problematic within rainshafts or updrafts/downdrafts associated with thunderstorms.
- **Icing.** When a balloon encounters clouds and precipitation zones where the temperature is below freezing, ice can form on the balloon and cause it to descend. Once the balloon descends below the freezing level, the ice melts and the balloon re-ascends. This causes the balloon to fluctuate up and down around the freezing level, and produces unrepresentative wind and thermodynamic data.

- **Poor radio navigation reception.** Not all sites have good radio navigation reception. If this technique is used to track the radiosonde, poor reception can produce uncertainties in the wind data. Poor reception will not affect the thermodynamic data.
- **Low-level wind problems.** Often the first few data points in a radiosonde wind profile tend to have more uncertainty due to initial tracking procedures or difficulties (see Section 9.1 for more details).

Sodar data can be rendered problematic by the following:

- **Passive noise sources (also called fixed echo reflections).** Passive noise occurs when nearby obstacles reflect the sodar's transmitted pulse. Depending on atmospheric conditions, wind speed, background noise, and signal processing techniques, the fixed echoes may reduce the velocity measured along a beam(s) or result in a velocity of zero. This problem is generally seen in the resultant winds as a rotation in direction and/or a decrease in speed at the affected altitude. Some manufacturers offer systems that have software designed to detect fixed echoes and effectively reject their influence. To further decrease the effect of the fixed echoes, additional acoustic shielding can be added to the system antenna.
- **Active noise sources (ambient noise interference).** Ambient noise can come from road traffic, fans or air conditioners, animals, insects, strong winds, etc. Loud broad-spectrum noise will decrease the SNR of the sodar and decrease the performance of the system. Careful siting of the instrument will help minimize this problem.
- **Unusually consistent winds at higher altitudes**. Barring meteorological explanations for this phenomenon, the most common cause is a local noise source that is incorrectly interpreted as a “real” Doppler shift. These winds typically occur near the top of the operating range of the sodar. A good means of identifying this problem is to allow the sodar to operate in a listen-only mode, without a transmit pulse, to see if winds are still reported. In some cases it may be necessary to make noise measurements in the specific operating range of the sodar to identify the noise source.
- **Reduced altitude coverage due to debris in the antenna.** In some instances, particularly after a precipitation event, the altitude coverage of the sodar may be significantly reduced due to debris in the antennas. In three axis systems, drain holes may become plugged with leaves or dirt and water, snow, or ice may accumulate in the antenna dishes. Similarly, some of the phased-array antenna systems have the transducers oriented vertically and are open to the environment. Blocked drain holes in the bottom of the transducers may prevent water from draining. Regular maintenance can prevent this type of problem.
- **Precipitation interference.** Precipitation, mostly rain, may affect the data collected by sodars. During rainfall events, the sodar may measure the fall speed of drops, which will produce unrealistic winds. In addition, the sound of the droplets hitting the antenna can increase the ambient noise levels and reduce the altitude coverage.
- **Low signal to noise ratio (SNR).** Conditions that produce low SNR can degrade the performance of a sodar. These conditions can be produced by high background noise, low turbulence and near neutral lapse rate conditions.

Data from radar wind profiler systems can be affected by several problems, including the following:

- **Interference from migrating birds.** Migrating birds can contaminate radar wind profiler signals and produce biases in the wind speed and direction measurements **[105]**. Birds act as large radar "targets," so that signals from birds overwhelm the weaker atmospheric signals. Consequently, the radar wind profiler measures bird motion instead of, or in addition to, atmospheric motion. Migrating birds have no effect on RASS. Birds generally migrate year-round along preferred flyways, with the peak migrations occurring at night during the spring and fall months **[106]**.

- **Precipitation interference.** Precipitation can affect the data collected by radar profilers operating at 915 MHZ and higher frequencies. During precipitation, the radar profiler measures the fall speed of rain drops or snow flakes. If the fall speeds are highly variable during the averaging period (e.g., convective rainfall), a vertical velocity correction can produce erroneous data.

- **Passive noise sources (ground clutter).** Passive noise interference is produced when a transmitted signal is reflected off an object instead of the atmosphere. The types of objects that reflect radar signals are trees, elevated overpasses, cars, buildings, airplanes, etc. Careful siting of the instrument can minimize the effects of ground clutter on the data. Both software and hardware techniques are also used to reduce the effects of ground clutter. However, under some atmospheric conditions (e.g., strong winds) and at some site locations, ground clutter can produce erroneous data. Data contaminated by ground clutter can be detected as a wind shift or a decrease in wind speed at affected altitudes. Additional information is provided in references **[107]** and **[108]**.

- **Velocity folding or aliasing.** Velocity folding occurs when the magnitude of the radial component of the true air velocity exceeds the maximum velocity that the instrument is capable of measuring, which is a function of sampling parameters **[109]**. Folding occurs during very strong winds (>20 m/s) and can be easily identified and flagged by automatic screening checks or during the manual review.

RASS systems are susceptible to several common problems including the following:

- **Vertical velocity correction.** Vertical motions can affect the RASS virtual temperature measurements. As discussed in Section 9.1, virtual temperature is determined by measuring the vertical speed of an upward-propagating sound pulse, which is a combination of the acoustic velocity and the atmospheric vertical velocity. If the atmospheric vertical velocity is non-zero and no correction is made for the vertical motion, it will bias the temperature measurement. As a rule of thumb, a vertical velocity of 1 ms^{-1} can alter a virtual temperature observation by 1.6°C.

- **Potential cold bias.** Recent inter-comparisons between RASS systems and radiosonde sounding systems have shown a bias in the lower sampling altitudes **[110]**. The RASS virtual temperatures are often slightly cooler (-0.5 to -1.0°C) than the reference radiosonde data. Work is currently underway to address this issue.

9.7 Data Processing and Management (DP&M)

An important component of any upper-air meteorological monitoring program is the processing, QA, management, and archival of the data. Each of these components is briefly discussed in this section and some general recommendations for data processing and management are provided. Additional guidance on data issues is provided in Chapter 8 of this guidance document.

9.7.1 Overview of Data Products

For radiosonde systems, the final data products typically consist of one or more ASCII files that contain the reduced thermodynamic data (pressure, temperature, relative humidity, dewpoint, etc.) and wind speed and wind direction as a function of altitude. Some radiosonde data systems store the thermodynamic information in one data file and the wind information in another, whereas other systems combine the observations into a single data file. Regardless of the approach used, the files containing the reduced wind and thermodynamic observations should be considered the final data products produced by the radiosonde sounding systems. Depending on the type of equipment, additional files may be created that include data reported in formats specifically intended for use by the NWS or other organizations, information on site location, sampling parameters, balloon position, etc. Typically, one set of files is created per sounding, that is, data from multiple soundings are not merged together.

For the remote sensing systems (sodar, radar wind profilers, RASS), the final data products usually consist of one or more ASCII files containing the averaged profiles of winds or virtual temperatures as a function of altitude. Supporting information provided with the reduced data products may include other variables such as horizontal and vertical meteorological velocity components (u, v, w), averaged return power, SNR or some other measure of signal strength, estimates of turbulence parameters (σ_w, σ_θ), mixing depth, etc. Typically one set of files is produced per 24-hour sampling period. These data files should be considered the final data products produced by this class of upper-air monitoring system. Other (lower-level) information generated by these systems may include, for example, the Doppler moment data and raw Doppler spectra. The quantity of information produced by the remote sensing systems usually requires that the lower-level data be stored in a binary format to conserve disk space. These data should be archived for backup purposes and to support post-processing or additional analyses of periods of interest.

9.7.2 Steps in DP&M

Data processing, validation, and management procedures for an upper-air meteorological monitoring program would typically include the following steps, which should be described in the QAPP:

- Collection and storage on-site (as appropriate) of the “raw” signals from the upper-air sensors, followed by real-time processing of the “raw” data by the data acquisition system to produce reduced, averaged profiles of the meteorological variables. The reduced data are stored on the data acquisition system's computer, usually in one or more ASCII files.

- Transfer of the reduced data to a central data processing facility at regular intervals (e.g., daily). Once the data are received at the central facility, they should be reviewed by an experienced data technician as soon as possible to verify the operational readiness of the upper-air site. Backup electronic copies of the data should be prepared and maintained on-site and off-site.

Data collected by the remote sensing systems can usually be obtained by polling the data system at a site from the central facility using a personal computer, modem, and standard telecommunications software. Other options that are available for communications with a remote upper-air site include leased-line telephone service, local or wide area network (LAN, WAN) connections, Internet access, and satellite telemetry. For immediate turnaround of radiosonde data, the upper-air operator can transfer the sounding data to the central facility using a personal computer equipped with a modem and communications software. There must be a bulletin board system (BBS) operating at the central facility, or some other means provided to receive the data (e.g., via an Internet access). Alternatively, if a one- or two-day delay is acceptable, the operator can mail the sounding data to the data center.

Please note that the initial review of the data is not very time consuming, but it is an extremely important component of a successful upper-air program. It is at this stage that most problems affecting data quality or data recovery will be detected. If the upper-air data are not reviewed at regular, frequent intervals, the risk of losing valuable information increases. If the data are reviewed frequently, then problems can be detected and corrected quickly, often the same day, thereby minimizing data losses. At a minimum, the operational readiness of an upper-air monitoring site should be checked regularly. Likewise, maintaining backup copies of the data at each stage of processing is extremely important. Backup copies should be kept at the central data processing facility and at a separate, off-site location(s) to ensure that no data are damaged or lost.

- Additional post-processing is performed as required (e.g., reformatting the data using a different database format than that produced by the data acquisition system) to produce the version of the data that will be subjected to final quality control validation.
- At this stage, the data are usually said to be at “Level 0” quality control validation, meaning that they are ready for quality control screening and final validation.
- Quantitative screening of the data can be performed using quality control software to identify outliers or other observations that are possibly in error or otherwise appear questionable.
- A final review of the data should be performed by an experienced meteorologist who understands the methods used to collect the data and who is knowledgeable about the kinds of meteorological conditions expected to be revealed in the data.

This is the process that brings the data to what is usually referred to as “Level 1” quality control validation, meaning that the data have been subjected to a qualitative (and often quantitative) review by experts to assess the accuracy, completeness, and internal consistency of the data. At this stage, data that have been determined to be in error are usually removed from the database, and quality control flags are assigned to the data values to indicate their validity. It is also at this stage that final calibrations should be applied to the data as necessary, as well as any changes required as the result of the system audits. Additional screening of the data based on

comparisons to other independent data sets may be performed, which is part of the process to bring the data to "Level 2" quality control.

- Some final processing may be necessary to convert the data to the format that will be used to submit the information to the final data archive.

Final documentation should be prepared that summarizes sampling strategies and conditions; describes the results of audits and any actions taken to address issues raised by the audits; identifies any problems that adversely affected data quality and/or completeness; and describes the contents and formats of the database. Typically, a copy (electronic and/or paper) of this documentation accompanies the submittal of the data to the final data archive. Once the above steps are completed, the data are ready to be submitted to the upper-air archive. Several options for creating an archive are available, ranging from a simple repository to complex database management systems (DBMS).

9.7.3 Data Archiving

Maintaining a complete and reliable data archive is an important component of a QAPP. Upper-air instruments, especially remote sensors, produce a large amount of data consisting of raw and reduced data. The amount of data from these upper-air sensors can require in excess of several gigabytes of computer storage space per site per year. A protocol for routinely archiving the data should be established.

Raw data are the most basic data elements from which the final data are produced. Archiving these data is important because at a later date the raw data may need to be reprocessed to account for problems, errors, or calibrations. In addition, future processing algorithms may become available to extract more information from the raw data. Raw data are generally stored on-site and should be archived as part of the operational checks. Data should be stored on convenient and reliable archive media such as diskette, tape, or optical disk. The primary archive should be stored in a central repository at the agency responsible for collecting the data. A second backup of the raw data should be made and stored off-site to ensure a backup if the primary data archive becomes corrupted or destroyed.

Reduced data, which are created from the raw data by averaging, interpolating, or other processing methods, should also be archived. Reduced data include hourly averaged winds and temperatures from remote sensors, and vertically averaged winds and thermodynamic data from radiosonde sounding systems. Data validation is performed on the reduced data to identify and flag erroneous and questionable data. Both the reduced and validated data should be routinely (e.g., weekly or monthly) archived onto digital media, with one copy stored onsite and a second copy stored offsite.

Other supporting information should be archived along with the data such as:

- Site and maintenance logs
- Audit and calibration reports
- Site information
- Log of changes made to the data and the data quality control codes

- Information that future users would need to decode, understand, and use the data
- Surface measurements and other relevant weather data

Data should be retained indefinitely because they are often used for modeling and analysis many years following their collection. Periodically, the integrity of the archive media should be checked to ensure that data will be readable and have not become corrupted. Data should be recycled by transfer from old to new media approximately every 5 to 10 years. If an archive is scheduled to be eliminated, potential users should be notified beforehand so that any important or useful information can be extracted or saved.

9.8 Recommendations for Upper-Air Data Collection

- *Suggested Data Quality Objectives (DOQs) for upper-air measurement systems are given in Table 9-5. DOQs for accuracy should be based on systematic differences; DOQs for precision should be based on the "comparability" statistic; DOQs for completeness should be based on percent data recovery.*
- *Site selection for upper-air measurement systems is best accomplished in consultation with vendors or users with expertise in such systems. Operators and site technicians of upper-air monitoring systems should receive appropriate training prior to or during system shake-down. Training should include instruction in instrument principles, operations, maintenance, troubleshooting, data interpretation and validation.*
- *System calibration and diagnostic checks of upper-air measurement systems should be performed at six month intervals, or in accordance with the manufacturer's recommendations, whichever is more frequent.*
- *Data capture for wind direction and wind speed from a sodar or radar wind profiler is defined somewhat differently than for more conventional instruments. The following definitions and requirements apply to databases generated by these instruments:*

  - *An averaging period (e.g., hourly) is considered valid if there are at least three valid levels of data for the period (independent of height).*

  - *If hourly average data are generated from sub-hourly intervals, the hourly values are considered valid if they consist for at least 30 minutes of valid sub- hourly data.*

  - *A valid level consists of all of the components needed to generate the horizontal wind vector.*
- *Remote sensing data should be reviewed at least weekly and preferably daily to assess the operational status of the system and to ensure that data are valid and reasonable.*

General recommendations for the processing, management, and archival of upper-air meteorological data include:

- *A consistent/standardized database format should be established and maintained, at a minimum for each individual monitoring program..*

- *The data archive should include raw, reduced, and validated data as well as other (low-level) data products, as appropriate (e.g., Doppler spectral moments data).*
- *The upper-air data should be validated to Level 1 before distribution.*
- *The data archive should be routinely backed up and checked for integrity.*
- *A secondary backup of the data should be kept at an alternate location, routinely checked for integrity, and periodically recycled onto new storage media.*

Table 9-1

Operating characteristics of upper-air meteorological monitoring systems.

VARIABLES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Measured	• p, T, RH • Vector winds (WS, WD)	• Vector winds (WS, WD) • u,v,w wind components	• Vector winds (WS, WD) • u,v,w wind components	• Virtual temperature (T_v) • w wind component
Derived	• Altitude • Moisture variables (dewpoint, mixing ratio, vapor pressure, etc.) • Potential temperature • Inversion base, top • Mixing depth	• Mixing depth • Dispersion statistics (σ_θ, σ_w)	• Mixing depth	• Inversion base, top • Mixing depth

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

PERFORMANCE CHARACTERISTICS	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Minimum Altitude	10-150 m	10-30 m	90-120 m	90-120 m
Maximum Altitude	5-15 km	0.2-2 km	1.5-4 km	0.5-1.5 km
Vertical Resolution	5-10 m (p, T, RH) 50-100 m (winds)	5-100 m	60-100 m	60-100 m
Temporal Resolution	Integration time 5 sec.-2 min. Resolution: intermittent (time between soundings 1.5-12 hr.)	Integration time: 11-60 min. Resolution: continuous	Integration time 15-60 min. Resolution: continuous	Integration time 5-10 min. Resolution: intermittent (time between profiles 5 min-1 hr.)

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

PERFORMANCE CHARACTERISTICS	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Systematic Difference	p: ± 0.5 mb T: ± 0.2°C RH: ± 10% U.V.: ± 0.5 to 1.0 ms^{-1}	WS: ± 0.2 to 1.0 ms^{-1} WD: ± 3-10°	WS: ± 1 ms^{-1} WD: ± 3-10°	± 1°C
Comparability	p (as height): ± 24 m T: ± 0.6°C T_d: ± 3.3°C WS: ± 3.1 ms^{-1} WD: ± 5-18°	WS: ± 0.5 to 2.0 ms^{-1} WD: ± 5-30°	WS: ± 2 ms^{-1} WD: ± 30°	± 1.5°C

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Siting Requirements	• Requires relatively flat area approx. 30x30 m (allow sufficient space to launch balloon). • Absence of tall objects (trees, power lines, towers) that could snag weather balloon.	• Requires relatively flat area approx. 20x20 m (allow space for audit equipment, met tower). • Absence of active noise sources. • Absence of passive noise (clutter) targets. • No neighbors within about 100-500 m (depending on the sodar) who would be bothered by noise.	• Requires relatively flat area approx. 20x20 m (allow space for audit equipment, met tower). • Lack of radar clutter targets extending more than 5° above the horizon in antenna pointing directions; 15° otherwise.	• No neighbors within about 1000 m who would be bothered by noise.

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Siting Logistics	• Balloon inflation shelter (e.g., small shed, tent, etc.) • Small (e.g., 8x12 ft.) equipment shelter, tied down, lightning protection • Security fence • 110/220v, 30 amp power service (usually required for air conditioning) • Communications service for data telemetry, voice. • May require FAA approval for operations at airports. • Instrument set-up can be completed in less than a day.	• Small (e.g., 8x12 ft.) equipment shelter, tied down, lightning protection • Security fence • 110/220v, 30 amp power service (usually required for air conditioning) • Communications service for data telemetry, voice. • Site will require 1-2 days to establish once trailer, power, etc. installed.	• Small (e.g., 8x12 ft.) equipment shelter, tied down, lightning protection. • Security fence • 110/220v, 30 amp power service (usually required for air conditioning) • Communications service for data telemetry, voice. • Site will require 2-3 days to establish once trailer, power, etc. installed.	• Add-on to radar profiler or sodar. No special additional logistical requirements. • Approx. 0.5-1 day needed to install and get operational.
Licensing	N/A	N/A	FCC license required	FCC license required

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Routine Operations	• Intermittent sampling; number of soundings varies with measurement objectives. Typically, one sounding per day near sunrise is a minimum sampling frequency; this will characterize the early morning stable boundary layer. Additional soundings are useful at mid-morning (ABL development), mid-to-late afternoon (full extent of daytime ABL), and at night (nocturnal ABL). • Requires expendables for each sounding (radiosonde, balloon, helium, parachute, light for night operations). • Manned operations; requires an operator for each sounding.	• Continuous sampling • Automated, unmanned • Daily checks of operational status via remote polling.	• Continuous sampling • Automated, unmanned • Daily checks of operational status via remote polling.	• Intermittent sampling every hour, or more often as needed. • Automated, unmanned • Daily checks of operational status via remote polling.

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Maintenance	• Bi-weekly barometer calibration checks • Daily back-ups • Back-up tracking device (e.g., optical theodolite) useful in case primary tracking system fails.	• Routine bi-weekly site inspections, servicing • Monthly on-site backups • Snow, ice removal in winter • Manufacturer-recommended spare parts	• Routine bi-weekly site inspections, servicing • Monthly on-site backups • Snow, ice removal in winter • Manufacturer-recommended spare parts	• Routine bi-weekly site inspections, servicing (follow SOP) • Monthly on-site backups • Snow, ice removal in winter • Manufacturer-recommended spare parts
Ground Truth	• Barometric pressure • T, RH • Radio theodolite oriented to true north, level	• Antenna orientation relative to true north • Antenna level	• Antenna orientation relative to true north • Antenna level	• Acoustic sources level • Antenna level

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
QA	• Acceptance test • Standard operating procedure (SOP) • Routine comparison with 10 m tower data • Annual system audit • Annual performance audit of ground truth instruments (e.g., barometer).	• Acceptance test • Standard operating procedure (SOP) • Routine comparison with 10 m tower data • Annual system audit • Annual intercomparison using complementary upper-air system.	• Acceptance test • Standard operating procedure (SOP) • Routine comparison with 10 m tower data • Annual system audit • Annual intercomparison using complementary upper-air system.	• Acceptance test • Standard operating procedure (SOP) • Routine comparison with 10 m tower data • Annual system audit • Annual intercomparison using complementary upper-air system.
Training	• Operators trained to perform soundings; usually requires a few days of classroom and on-site training. • Final data review should be performed by a meteorologist familiar with the instrument systems used.	• Site technicians trained to service equipment; usually requires 1-2 days of on-site training. • Data processing technician trained to poll site, retrieve data, review operational status, troubleshoot problems. • Final data review should be performed by a meteorologist familiar with the instrument systems used.	• Site technicians trained to service equipment; usually requires 1-2 days of on-site training. • Data processing technician trained to poll site, retrieve data, review operational status, troubleshoot problems. • Final data review should be performed by a meteorologist familiar with the instrument systems used.	• Site technicians trained to service equipment; usually requires 1-2 days of on-site training. • Data processing technician trained to poll site, retrieve data, review operational status, troubleshoot problems. • Final data review should be performed by a meteorologist familiar with the instrument systems used.

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Data Processing	• Reduce data on-site, ensure proper operations. • Bring final data to at least Level 1 QC validation (see text). • 100 Kb - 1 Mb/sounding	• Use vertical velocity correction (see text). • Bring final data to at least Level 1 QC validation (see text). • 100 Kb/day	• Use vertical velocity correction (see text). • Bring final data to at least Level 1 QC validation (see text). • 150 Kb-1 Mb /day	• Use vertical velocity correction (see text). • Bring final data to at least Level 1 QC validation (see text). • 20 Kb/day

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

STRENGTHS	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
	• *In situ* measurements • Deep profiles, high data recovery rates to extended altitudes. • Measures atmospheric moisture • Data compatible with global upper-air network.	• Samples lower parts of ABL • Continuous • Smaller sample volumes (finer vertical resolution). • Fixed reference frame • Useful in complex terrain to measure winds at plume heights.	• Samples through full extent of ABL • Continuous • Data recovery not affected by high wind speeds. • Performance improves with increasing RH. • Fixed reference frame	• Provides high time resolution of temperature profiles in ABL. • Measures T_v • Fixed reference frame

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

LIMITATIONS	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
	• Not continuous • Manned operations • Lowest altitude at which good winds are reported can be 200-300 m above ground level depending on tracking system, signal strength, operator training. • Balloon drifts with wind, producing moving reference frame for measurements. • Wet bulb not as reliable as carbon hygristor for measuring frost point. • Launching problematic during thunderstorms. • Subject to icing. • LORAN radio navigation system being discontinued.	• Altitude coverage may not extend through full depth of daytime ABL. • Altitude coverage may be limited at night due to nocturnal inversion. • Interference from active noise sources. • Interference from precipitation. • High wind speeds reduce altitude coverage. • Performance degrades (lower altitude coverage) with low RH. • Nuisance effects from transmitted noise. • Multiple component statistics such as σ_θ not reliable.	• Interference from precipitation. • Interference from migrating birds. • Lowest altitude sampled ~100 m above ground level. • May be subject to ground clutter. • Larger sample volumes (coarser vertical resolution). • Performance degrades (lower altitude coverage) at low RH.	• T_v may need to be converted to T. • Nuisance effects from transmitted noise. • Altitude coverage may not extend through full depth of daytime ABL. • Error sources exist that can produce biases on the order of 0.5-1° C, which may be corrected during post-processing.

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This document provides EPA's guidance for the collection and processing of meteorological data for use in regulatory dispersion modeling and is the basis for the regulatory review of proposed meteorological monitoring plans by the EPA Regions and the States. The document contains comprehensive and detailed guidance for meteorological measurement programs, covering the initial design and siting of a system, through data recording and processing.

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and

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FOREWORD

Many individuals were involved in the preparation of this document and should be contacted if any questions arise in the application of the guideline.

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1. INTRODUCTION

The Clean Air Act Amendments of 1977, Part D, Prevention of Significant Deterioration, require that certain new major stationary sources and major modifications be subject to a preconstruction review which includes an ambient air quality analysis. Furthermore, the Act requires that an analysis be conducted in accordance with regulations promulgated by the EPA. In this regard, the Agency promulgated PSD regulations [1] on June 19, 1978, which included ambient monitoring requirements. Guidelines were published in May 1978 [2] to discuss monitoring for PSD purposes. However, in response to the June 18, 1979 preliminary Court Decision (Alabama Power Company v. Costle, 13 ERC 1225), EPA proposed revised PSD regulations [3] on September 5, 1979. The final court decision was rendered December 14, 1979 [4]. Based on the public comments to the September 5, 1979 proposed PSD regulations and the December 14, 1979 court decision, EPA promulgated new PSD regulations on August 7, 1980. Some of the pertinent provisions of the 1980 PSD regulations that affect PSD monitoring are discussed below:

(a) Potential to emit.

The PSD regulations retain the requirement that new major stationary sources would be subject to a new source review on the basis of potential to emit. However, the annual emission potential of a source will be determined after the application of air pollution controls rather than before controls as was generally done under the 1978 regulations [1].

(b) De minimis cutoffs.

The PSD regulations will exempt on a pollutant specific basis major modifications and new major stationary sources from all monitoring requirements when emissions of a particular pollutant are below a specific significant emission rate, unless the source is near a Class I area. Also included are significant air quality levels which may be used to exempt sources or modifications from PSD monitoring when the air quality impacts from the sources or modifications are below specified values.

(c) Noncriteria pollutants.

The 1978 PSD regulations [1] required monitoring only for those pollutants for which national ambient air quality standards exist. However, there are a number of pollutants for which no ambient standards exist (noncriteria pollutants) but which are regulated under new source performance standards and national emission standards for hazardous pollutants. The 1980 regulations [5] require an ambient air quality analysis for all regulated pollutants emitted in significant amounts. This analysis will generally be based on modeling the impact of the pollutants in lieu of collecting monitoring data.

(d) Preconstruction monitoring.

A list of air quality concentrations is included in the PSD regulations as criteria for generally exempting proposed sources or modifications from collecting monitoring data. Basically, monitoring data will be required if the existing air quality and the impact of the proposed source or modification is equal to or greater than these concentrations. In certain cases, even though the air quality impact or background air quality may be less than these concentrations, monitoring data may be required if the proposed source or modification will impact a Class I area, nonattainment area, or area where the PSD increment is violated.

(e) Postconstruction monitoring.

The PSD regulations include authority to require postconstruction monitoring. In general, EPA may require postconstruction monitoring from large sources or sources whose impacts will threaten standards or PSD increments. The permit granting authority will make this decision on a case-by-case basis.

In 1987 [6] EPA promulgated revisions to the National Ambient Air Quality Stardards (NAAQS) for Particulate Matter. Also, revisions were promulgated to revise the PSD regulations to account for the NAAQS changes. The PM_{10} amendments will not require any new data gathering requirements beyond the 1980 PSD requirements for PSD applications submitted not later than 10 months after the effective date of the 1987 PSD amendments. New monitoring requirements for PM_{10} will be phased in for PSD applications submitted greater than 10 and and less than 24 months after the effective date of the 1987 PSD amendments. In addition, all new monitoring requirements for PM_{10} will be in effect 24 months after the effective date of the PSD amendments.

Because of the revisions to the PSD regulations, this guideline has been modified to reflect such revisions. The purpose of this guideline is to address those items or activities which are considered essential in conducting an ambient air quality monitoring program. Guidance is given for designing a PSD air quality monitoring network as well as the operational details such as sampling procedures and methods, duration of sampling, quality assurance procedures, etc. Guidance is also given for a meteorological monitoring program as well as the specifications for meteorological instrumentation and quality assurance procedures.

An appendix is included to show how the ambient air quality analysis fits in the overall PSD requirements. Flow diagrams are presented to aid a proposed source or modification in assessing if monitoring data may be required.

General adherence to the guidance contained in this document should ensure consistency in implementing the PSD monitoring regulations.

2. GENERAL REQUIREMENTS AND CONSIDERATIONS

2.1 Monitoring Data Rationale

The court decision [4] has affirmed the Congressional intent in the Clean Air Act as it relates to PSD monitoring requirements. The court ruled that section 165(e)(1) of the Clean Air Act requires that an air quality analysis be conducted for each pollutant subject to regulation under the Act before a major stationary source or major modification could construct. This analysis may be accomplished by the use of modeling and/or monitoring the air quality. EPA has discretion in specifying the choice of either monitoring or modeling, consistent with the provisions in section 165(e)(2). As will be discussed later, modeling will be used in most cases for the analysis for the noncriteria pollutants.

The court ruled that section 165(e)(2) of the Clean Air Act requires that continuous preconstruction air quality monitoring data must be collected to determine whether emissions from a source will result in exceeding the National Ambient Air Quality Standards (NAAQS). Further, the data could be used to verify the accuracy of the modeling estimates since modeling will be the principal mechanism to determine whether emissions from the proposed source or modification will result in exceeding allowable increments. In regard to monitoring requirements, the court stated that EPA had the authority to exempt de minimis situations.

Postconstruction monitoring data requirements are addressed in section 165(a)(7) of the Clean Air Act. Sources may have to conduct such monitoring to determine the air quality effect its emissions may have on the area it impacts. EPA has the discretion of requiring monitoring data and the court stated that guidelines could be prepared to show the circumstances that may require postconstruction monitoring data.

In view of the provisions of sections 165(e)(1), 165(e)(2), and 165(a)(7) of the Clean Air Act, the de minimis concept, and sections of the final PSD regulations, Sections 2.1.1, 2.1.2 and 2.1.3 present the basic rationale which generally will be followed to determine when monitoring data will or will not be required. It should be noted that the subsequent use of "monitoring data" refers to either the use of existing representative air quality data or monitoring the existing air quality.

Additional discussion and flow diagrams are presented in Appendix A of this guideline which show various decision points leading to a determination as to when monitoring data will or will not be required. Also, these procedures indicate at what points a modeling analysis must be performed.

2.1.1 Criteria Pollutants - Preconstruction Phase

For the criteria pollutants (SO_2, CO, and NO_2) continuous air quality monitoring data must, in general, be used to establish existing air quality

concentrations in the vicinity of the proposed source or modification. For VOC emissions, continuous ozone monitoring data must be used to establish existing air quality concentrations in the vicinity of the proposed source or modification. For PM_{10} and lead, the 24-hour manual method will be used to establish the existing air quality concentrations. However, no preconstruction monitoring data will generally be required if the ambient air quality concentration before construction is less than the significant monitoring concentrations. (The significant monitoring concentrations for each pollutant are shown in Table A-2 in the appendix to this guideline.) To require monitoring data where the air quality concentration of a pollutant is less than these values would be questionable because these low level concentrations cannot reasonably be determined because of measurement errors. These measurement errors may consist of errors in sample collection, analytical measurement, calibration, and interferences.

Cases where the projected impact of the source or modification is less than the significant monitoring concentrations would also generally be exempt from preconstruction monitoring data, consistent with the de minimis concept. [40 CFR 51.24(i)(8) and 40 CFR 52.21(i)(8)].

The one exception to the de minimis exemption occurs when a proposed source or modification would adversely impact on a Class I area or would pose a threat to the remaining allowable increment or NAAQS. For those situations where the air quality concentration before construction is near the significant monitoring concentration, and there are uncertainties associated with this air quality situation, then preconstruction air quality monitoring data may be required. These situations must be evaluated on a case-by-case basis by the permit granting authority before a final decision is made.

2.1.2 Criteria Pollutants - Postconstruction Phase

EPA has discretion in requiring postconstruction monitoring data under section 165(a)(7) of the Clean Air Act and in general will not require postconstruction monitoring data. However, to require air quality monitoring data implies that the permit granting authority will have valid reasons for the data and, in fact, will use the data after it is collected. Generally, this will be applied to large sources or sources whose impact will threaten the standards or PSD increments. Examples of when a permit granting authority may require postconstruction monitoring data may include:

a. NAAQS are threatened - The postconstruction air quality is projected to be so close to the NAAQS that monitoring is needed to certify attainment or to trigger appropriate SIP related actions if nonattainment results.

b. Source impact is uncertain or unknown - Factors such as complex terrain, fugitive emissions, and other uncertainties in source or emission characteristics result in significant uncertainties about the projected

impact of the source or modification. Postconstruction data is justified as a permit condition on the basis that model refinement is necessary to assess the impact of future sources of a similar type and configuration.

2.1.3 Noncriteria Pollutants - Preconstruction and Postconstruction Phase

Consistent with section 165(e)(1) of the Clean Air Act, EPA believes that an analysis based on modeling of the impact of noncriteria pollutants (including TSP) on the air quality should generally be used in lieu of monitoring data. The permit granting authority, however, does have the discretion of requiring preconstruction and postconstruction monitoring data. Before a permit granting authority exercises its discretion in requiring monitoring data, there should be an acceptable measurement method approved by EPA (see Section 2.6) and the concentrations would generally be equal to or greater than the significant monitoring concentrations (shown in Table A-2 of the appendix).

A permit granting authority may require monitoring data in cases such as (a) where a State or other jurisdiction has a standard for a noncriteria pollutant and the emissions from the proposed source or modification pose a threat to the standard, (b) where the reliability of emission data used as input to modeling existing sources is highly questionable, especially for the pollutants regulated under the national emission standards for hazardous pollutants, and (c) where available models or complex terrain make it difficult to estimate air quality or impact of the proposed source or modification.

2.2 Monitoring Objective and Data Uses

The basic objective of PSD monitoring is to determine the effect emissions from a source are having or may have on the air quality in any area that may be affected by the emission. Principal uses of the data are as follows:

(a) To establish background air quality concentrations in the vicinity of the proposed source or modification. These background levels are important in determining whether the air quality before or after construction are or will be approaching or exceeding the NAAQS or PSD increment.

(b) To validate and refine models. The data will be helpful in verifying the accuracy of the modeling estimates.

2.3 VOC and O_3 Monitoring Requirements

The previous 0.24 ppm nonmethane organic compound (NMOC) standard, which was used as a guide for developing State Implementation Plans to attain the O_3 ambient standard, has been rescinded. However, VOC emissions are the precursors in the formation of ozone. Consequently, any new source or modified existing source located in an unclassified or attainment area for ozone that is equal to or greater than 100 tons per year of VOC emissions will be required to monitor ozone. VOC monitoring will not be required.

2.4 Use of Representative Air Quality Data

The use of existing representative air quality data was one of the options discussed in Section 2.1 for monitoring data. In determining whether the data are representative, three major items which need to be considered are monitor location, quality of the data, and currentness of the data.

2.4.1 Monitor Location

The existing monitoring data should be representative of three types of areas: (1) the location(s) of maximum concentration increase from the proposed source or modification, (2) the location(s) of the maximum air pollutant concentration from existing sources, and (3) the location(s) of the maximum impact area, i.e., where the maximum pollutant concentration would hypothetically occur based on the combined effect of existing sources and the proposed new source or modification. Basically, the locations and size of the three types of areas are determined through the application of air quality models. The areas of maximum concentration or maximum combined impact vary in size and are influenced by factors such as the size and relative distribution of ground level and elevated sources, the averaging times of concern, and the distances between impact areas and contributing sources.

In situations where there is no existing monitor in the modeled areas, monitors located outside these three types of areas may or may not be used. Each determination must be made on a case-by-case basis. In order to clarify EPA's intent regarding the use of existing monitoring data, some examples are included to demonstrate the overall intent.

(a) Case I - If the proposed source or modification will be constructed in an area that is generally free from the impact of other point sources and area sources associated with human activities, then monitoring data from a "regional" site may be used as representative data. Such a site could be out of the maximum impact area, but must be similar in nature to the impact area. This site would be characteristic of air quality across a broad region including that in which the proposed source or modification is located. The intent of EPA is to limit the use of these "regional" sites to relatively remote areas, and not to use them in areas of multisource emissions or areas of complex terrain.

(b) Case II - If the proposed construction will be in an area of multisource emissions and basically flat terrain, then the proposed source or modification may propose the use of existing data at nearby monitoring sites if either of the following criteria are met.

1. The existing monitor is within 10 km of the points of proposed emissions, or

2. The existing monitor is within or not farther than 1 km away from either the area(s) of the maximum air pollutant concentration from existing sources or the area(s) of the combined maximum impact from existing and proposed sources.

If the existing monitor(s) meets either of the above two conditions, the data could be used together with the model estimates to determine the concentrations at all three types of areas discussed earlier in this section.

As an example of the first criterion, if an existing monitor is located within 10 km from the points of proposed emissions but not within the boundaries of the modeled areas of either of the three locations noted above, the data could be used together with model estimates to determine the concentrations at the three types of required area.

The next example applies to the second criterion. In evaluating the adequacy of the location of existing monitors, the applicant must first, through modeling, determine the significant ambient impact area of the proposed source. In general, except for impact on Class I areas, the application of air quality models for the purpose of determining significant ambient impact would be limited to 50 km downwind of the source or to that point where the concentration from the source falls below the levels shown in Table A-3 of the Appendix. For Class I areas, a significant impact is 1 ug/m^3 (24-hr) for PM_{10} and SO_2. The applicant would then identify within this significant impact area the area(s) of the maximum air pollutant concentration from existing sources and the area(s) of the combined maximum impact from existing and proposed sources. The area(s) of estimated maximum concentration from existing sources or the estimated maximum combined impact area(s) are determined as follows: First, within the modeled significant ambient impact area, estimate the point of maximum concentration from existing sources, and the point of combined maximum impact (existing and proposed source). Using these concentration values, determine the areas enclosed by air quality concentration isopleths equal to or greater than one half of the respective estimated maximum concentration. An existing monitor located within or not farther than 1 km away from of any of these areas can yield representative data.

The rationale for considering the use of existing data collected from monitors satisfying the above criteria is that modelers have a reasonable degree of confidence in the modeling results within the 10 km distance and the maximum concentrations from most sources are likely to occur within this distance. Generally, the modeling results in this flat terrain case may under or over predict by a factor of two, and thus the actual maximum impact from the source(s) could occur at points where the model predicts one half of this impact. Data collected within or not farther than 1 km from areas may be considered as representative.

(c) Case III - If the proposed construction will be in an area of multisource emissions and in areas of complex terrain, aerodynamic downwash complications, or land/water interface situations, existing data could only

be used for PSD purposes if it were collected (1) at the modeled location(s) of the maximum air pollution concentration from existing sources, (2) at the location(s) of the maximum concentration increase from the proposed construction, and (3) at the location(s) of the maximum impact area. If a monitor is located at only one of the locations mentioned above and the locations do not coincide, the source would have to monitor at the other locations.

It must be emphasized that the permit granting authority may choose not to accept data proposed under the cases discussed above. This may occur because of additional factors, especially in Case II which were not discussed but must be considered, such as uncertainties in data bases for modeling and high estimates of existing air quality resulting in possible threats to the applicable standards. Because of such situations, the permit granting authority must review each proposal on a case-by-case basis to determine if the use of existing data will be acceptable. It is important for the proposed source or modification to meet with the permit granting authority to discuss any proposed use of existing data. If the data are not acceptable, then a monitoring program would have to be started to collect the necessary data.

2.4.2 Data Quality

The monitoring data should be of similar quality as would be obtained if the applicant monitored according to the PSD requirements. As a minimum, this would mean:

1. The monitoring data were collected with continuous instrumentation. No bubbler data should be included. See Section 2.7 for frequency of particulate pollutant sampling.

2. The applicant should be able to produce records of the quality control performed during the time period at which the data were collected. Such quality control records should include calibration, zero and span checks, and control checks. In addition, quality control procedures should be a minimum specified in the instrument manufacturer's operation and instruction manual.

3. Historical data that were gathered from monitors which were operated in conformance with Appendix A or B of the Part 58 regulations [7] would satisfy the quality assurance requirements.

4. The calibration and span gases (for CO, SO_2 and NO_2) should be working standards certified by comparison to a National Bureau of Standards gaseous Standard Reference Material.

5. The data recovery should be 80 percent of the data possible during the information effort.

2.4.3 Currentness of Data

The air quality monitoring data should be current. Generally, this would mean for the preconstruction phase that the data must have been collected in the 3-year period preceding the permit application, provided the data are still representative of current conditions. When such data are required, the noncriteria pollutant data must also have been collected in the 3-year period preceding the permit application provided that an acceptable measurement method was used. For the postconstruction phase, the data must be collected after the source or modification becomes operational.

2.4.4 Provisions for PM_{10} and TSP in Transition Period of 1987 PSD Amendments

Section 2.5.2 discusses the use of existing representative air quality data for P_{10} and TSP during the phasing in of the 1987 PSD amendments for particulate matter. References are cited for using existing nonreference PM_{10} and/or PM_{15} data where available, or TSP data. Existing representative air quality data for PM_{10} collected more than 12 months after the effective date of the 1987 PSD amendments must have been collected using reference or equivalent PM_{10} method samplers.

2.5 Duration of Monitoring

2.5.1 Normal Conditions

If a source must monitor because representative air quality data are not available for the preconstruction monitoring data requirement, then monitoring generally must be conducted for at least 1 year prior to submission of the application to construct. Also, if a source decides to monitor because representative air quality data are not available for the postconstruction monitoring data requirement, then monitoring must also be conducted for at least 1 year after the source or modification becomes operational. However, under some circumstances, less than 1 year of air quality data may be acceptable for the preconstruction and postconstruction phases. This will vary according to the pollutant being studied. For all pollutants, less than a full year will be acceptable if the applicant demonstrates through historical data or dispersion modeling that the data are obtained during a time period when maximum air quality levels can be expected. However, a minimum of 4 months of air quality data will be required. As discussed in Section 2.1.3, monitoring for noncriteria pollutants will generally not be required.

Special attention needs to be given to the duration of monitoring for ozone. Ozone monitoring will still be required during the time period when maximum ozone concentrations will be expected. Temperature is one of the factors that affect ozone concentrations, and the maximum ozone concentrations will generally occur during the warmest 4 months of the year, i.e., June-September. However, historical monitoring data have shown that the maximum

yearly ozone concentration for some areas may not occur from June-September. Therefore, ozone monitoring will also be required for those months when historical ozone data have shown that the yearly maximum ozone concentrations have occurred during months other than the warmest 4 months of the year. This requirement is in addition to monitoring during the warmest 4 months of the year. If there is an interval of time between the warmest 4 months of the year and month where historical monitoring data have shown that the maximum yearly ozone concentration has occurred, then monitoring must also be conducted during that interval. For example, suppose historical data have shown the maximum yearly ozone concentration for at least 1 year occurred in April. Also, suppose the warmest 4 months for that particular area occurred June-September. In such cases, ozone monitoring would be required for April (previous maximum concentration month), May (interval month), and June-September (warmest 4 months).

Some situations may occur where a source owner or operator may not operate a new source or modification at the rated capacity applied for in the PSD permit. Generally, the postconstruction monitoring should not begin until the source is operating at a rate equal to or greater than 50 percent of its design capacity. However, in no case should the postconstruction monitoring be started later than 2 years after the start-up of the new source or modification.

If the permit granting authority has determined that less than 1 year of monitoring data is permissible, the source must agree to use the maximum values collected over this short period for comparison to all applicable short-term standards, and the average value for the short period as the equivalent of the annual standard.

It should also be noted that the above discussion of less than 1 year of data pertains to air quality data, not meteorological data. When the air quality impact must be determined using a dispersion model, the preferred meteorological data base is at least 1 year of on-site data. Although less than 1 year of data may be sufficient to determine the acceptability for a model, once the model has been accepted, a full year of meteorological data must be used in the PSD analysis.

2.5.2 Transition Period for PM_{10} and TSP

The 1987 PSD regulatory changes for particulate matter [6] provide for a transition period for phasing in the PM_{10} monitoring data requirements. The term "monitoring data" was previously defined in Section 2.1 as the use of existing representative air quality data or monitoring to determine the existing air quality.

2.5.2.1 Transition Within 10 Months After Effective Date of PM_{10} Amendments - The first provision of the regulations concerning a transition period is in section 52.21(i)(11)(i) and relates to applications for a PSD permit submitted not later than 10 months after the effective date of the 1987 PSD amendments. During this 10-month period, the permit granting authority has the discretion

of waiving the preconstruction monitoring data requirements for the ambient air quality analysis discussed in Appendix A of this guideline. In all cases no applicant would be required to initiate monitoring during this period. However, the requirement to use existing air quality data would be discretionary. The discretion would be based in part on the availability of existing air quality data which could include total suspended particulate matter data, PM_{10} data, as well as inhalable particulate matter (PM_{15}) data. The PM_{15} data would be from samplers with inlets designed for a 50 percent collective efficiency at 15 um. The PM_{15} data could be from dichotomous samplers or high volume samplers with a size selective inlet of 15 um.

(a) Comparing Representative Air Quality Data to PM_{10} NAAQS. In situations where existing PM_{10} and/or PM_{15} data are available, the data may be used for describing the existing air quality levels for comparison with the PM_{10} NAAQS. Reference [8] describes procedures for estimating ambient PM_{10} concentrations from PM_{15} ambient air measurements. The PM_{15} data multiplied by a correction factor of 0.8 may be assumed to be equivalent to PM_{10}. Existing TSP data may only be used as a "one-for-one" substitute for comparison to the PM_{10} NAAQS.

Concerning the priorities for using existing air quality data, the first preference is to use ambient PM_{10} data. The second preference is to use inhalable particulate (PM_{15}) measurements obtained with a dichotomous sampler or a size selective high volume sampler. The third preference is to use total suspended particulte (TSP) data. Also, combinations of the above data may be used.

2.5.2.2 Transition During 10-16 Months After Effective Date of PM_{10} Amendments - The second provision of the regulations concerning a transition period is in section 52.21(i)(11)(ii) and relates to applications for a PSD permit submitted more than 10 months and no later than 16 months after the effective date of the 1987 PSD amendments. If preconstruction monitoring data are required in the ambient air quality analysis during this 10 to 16-month period, the applicant must use representative air quality data or collect monitoring data.

(a) Comparing Preconstruction Air Quality Data to PM_{10} NAAQS. Existing representative PM_{10} and/or PM_{15} air quality data may be used if available. The priorities and calculations for using these data were described in Section 2.5.2.1. Existing TSP data cannot be used during during this transition period.

If the applicant collects new PM_{10} and/or PM_{15} monitoring data, the data should have been collected from the date 6 months after the effective date of the 1987 PSD amendments to the time the PSD application becomes otherwise complete. The preferences for PM_{10} and PM_{15} data were previously discussed.

(b) Other Considerations and Explanations. As discussed in Section 2.5.1, less than the maximum amount of data (10 months in this case) monitoring data will be acceptable if the applicant demonstrates, through

historical data or dispersion modeling, that the data would be obtained during a time period when the maximum air quality can be expected. The minimum of 4 months of air quality data would still be required. The assumptions for the 10-month figure were derived by assuming that 5 months are needed for instrument and equipment procurement, 1 month to install the equipment, calibrate and ensure satisfactory operation, and a minimum of 4 months of monitoring data. The upper range of 16 months after the effective date for use of non-reference PM_{10} monitoring is based on the assumption that within 11 months after the effective date, reference or equivalent method samplers for PM_{10} would be designated by EPA and would be commercially available. Furthermore, 1 month would be needed to install the equipment, calibrate, and ensure satisfactory operation, and a minimum of 4 months would be needed for gathering monitoring data.

2.5.2.3 Transition During 16-24 Months After Effective Date of PM_{10} Amendments - The third transition period provision of the amendments is in section 52.21(m)(1)(vii) and relates to applications for a PSD permit submitted more than 16 months and not later than 24 months after the effective date of the 1987 PSD amendments. If preconstruction monitoring data are required in the ambient air quality analysis during this 16 to 24-month period, the applicant must use representative air quality data or collect monitoring data.

(a) Comparing Preconstruction Air Quality Data to PM_{10} NAAQS. If existing representative PM_{10} and/or PM_{15} air quality data are available they may be used. The priorities and calculations for using these data were described in Section 2.5.2.1. Existing TSP data cannot be used during this transition period. If no PM_{10} or PM_{15} representative air quality data are available, the applicant will have to collect monitoring data using only reference or equivalent PM_{10} method samplers. The sampling must be conducted for at least 12 months during the period from 12 months after the effective date to the time when the application is completed, except if the permit granting authority determines that a complete and adequate analysis can be accomplished with monitoring data over a shorter period (but in no case less than 4 months).

2.5.2.4 Period Following 24 Months After Effective Date of PM_{10} Amendments - For applications for a PSD permit submitted later than 24 months after the effective date, the transition period would no longer be in effect. If preconstruction monitoring data are required in the ambient air quality analysis, the applicant must use representative air quality data or collect monitoring data.

(a) Comparing Preconstruction Air Quality Data to PM_{10} NAAQS. If existing representative PM_{10} air quality data are available, they may be used. However, existing PM_{10} representative air quality data collected later than 24 months after the effective date of the 1987 PSD amendments must have been collected using reference or equivalent PM_{10} method samplers. If no PM_{10} representative air quality data are available, the applicant will have to collect monitoring data using only reference or equivalent PM_{10} method samplers.

2.6 Sampling Methods and Procedures

(a) Criteria pollutants.

All ambient air quality monitoring must be done with continuous Reference or Equivalent Methods, with the exception of particulate matter and lead for which continuous Reference or Equivalent Methods do not exist. For particulate matter and lead, samples must be taken in accordance with the Reference Method. The Reference Methods are described in 40 CFR 50. A list of designated continuous Reference or Equivalent Methods can be obtained by writing Environmental Monitoring Systems Laboratory, Department E (MD-76), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711.

(b) PM_{10} Transition for Non-reference Methods

As discussed in Section 2.5.2, non-reference monitors for PM_{10} may be used for applications submitted not later than 16 months after the effective date of the 1987 PSD amendments. These could include PM_{10} monitors as well as inhalable particulate matter (PM_{15}) monitors. The PM_{15} monitors could be dichotomous monitors or high volume monitors with a size selective inlet of 15 um.

(c) Noncriteria pollutants.

For noncriteria pollutants, a list of acceptable measurement methods is available upon request by writing Environmental Monitoring Systems Laboratory, Quality Assurance Division (MD-77), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711. This list of acceptable methods will be reviewed at least annually and are available from the above address. Measurement methods considered candidates for the noncriteria pollutant list should be brought to the attention of EPA at the address given above.

2.7 Frequency of Sampling

For all gaseous pollutants and for all meteorological parameters, continuous analyzers must be used. Thus, continuous sampling (over the time period determined necessary) is required. For particulate pollutants, except for PM_{10}, daily sampling (i.e., one sample every 24 hours) is required except in areas where the applicant can demonstrate that significant pollutant variability is not expected. In these situations, a sampling schedule less frequent than every day would be permitted. However, a minimum of one sample every 6 days will be required for these areas. The sampling frequency would apply to both preconstruction and postconstruction monitoring.

The sampling frequency for PM_{10} samplers is determined by the PM_{10}, PM_{15}, or TSP concentrations relative to the PM_{10} NAAQS. The philosophy is to use existing data where possible to determine the PM_{10} sampling frequency.

The frequencies discussed below are consistent with the Part 58 sampling frequencies [6]. If PM_{10} data are available but not from the locations as specified in Section 2.4.1, then modeling could be used in conjunction with the data to estimate the PM_{10} concentrations in the appropriate sampling area(s) to determine the PM_{10} sampling frequency. If these estimated concentrations were < 80 percent of the PM_{10} NAAQS, then a minimum of one sample every 6 days would be required for PM_{10} monitors; for $\geq$80 - <90 percent of the PM_{10} NAAQS, a minimum of one sample every other day would be required; and for $\geq$90 percent of the PM_{10} NAAQS every day sampling would be required. PM_{15} data would be treated the same way except the data must be multiplied by a correction factor of 0.8 to be equivalent to PM_{10}.

Reference [8] describes how TSP data may also be used to estimate the probability of exceeding the PM_{10} NAAQS in the appropriate sampling area(s) for purposes of determining the PM_{10} sampling frequency. If the probabilities are < .20 of the PM_{10} NAAQS, then a minimum of one sample every 6 days would be required for PM_{10} monitors; for $\geq$.20 - <.50 probabilities, a minimum of one sample every other day would be required; and for $\geq$.50 probabilities, every day sampling would be required. These probability intervals are in line with the percent of the NAAQS intervals specified when using PM_{10} data.

In those cases where no PM_{10}, PM_{15}, or TSP data are available to determine the PM_{10} sampling frequency, the PM_{10} expected concentrations could be estimated by modeling. These estimated concentrations would be used to calculate the percentage of the PM_{10} NAAQS and the resulting PM_{10} sampling frequency as discussed above for the cases where PM_{10} data were available.

2.8 Monitoring Plan

A monitoring plan prepared by the source should be submitted to and approved by the permit granting authority before any PSD monitoring begins. Note that approval of the monitoring plan before a monitoring program is started is not a requirement. However, since the network size and station locations are determined on a case-by-case basis, it would be prudent for the owner or operator to seek review of the network and the overall monitoring plan from the permit granting authority prior to collecting data. This review could avoid delays in the processing of the permit application and could also result in the elimination of any unnecessary monitoring. Delays may result from insufficient, inadequate, poor, or unknown quality data. Table 1 lists the types of information that should be included in the monitoring plan.

2.9 Meteorological Parameters and Measurement Methods

Meteorological data will be required for input to dispersion models used in analyzing the impact of the proposed new source or modification on ambient air quality and the analyses of effects on soil, vegetation, and visibility in the vicinity of the proposed source. In some cases, representative data are available from sources such as the National

Weather Service. However, in some situations, on-site data collection will be required. The meteorological monitoring and instrumentation considerations are discussed in Sections 5 and 6.

TABLE 1. MINIMUM CONTENTS OF A MONITORING PLAN

I. SOURCE ENVIRONMENT DESCRIPTION (within 2 km of source)

- o topographical description
- o land-use description
- o topographical map of source and environs (including location of existing stationary sources, roadways, and monitoring sites)
- o climatological description
- o quarterly wind roses (from meteorological data collected at the source or other representative meteorological data)

II. SAMPLING PROGRAM DESCRIPTION

- o time period for which the pollutant(s) will be measured
- o rationale for location of monitors (include modeling results and analysis of existing soures in the area)
- o rationale for joint utilization of monitoring network by other PSD sources

III. MONITOR SITE DESCRIPTION

- o Universal Transverse Mercator (UTM) coordinates
- o height of sampler (air intake) above ground
- o distance from obstructions and heights of obstructions
- o distance from other sources (stationary and mobile)
- o photographs of each site (five photos: one in each cardinal direction looking out from each existing sampler or where a future sampler will be located, and one closeup of each existing sampler or where a future sampler will be located. Ground cover should be included in the closeup photograph.)

IV. MONITOR DESCRIPTION

- o name of manufacturer
- o description of calibration system to be used
- o type of flow control and flow recorder

V. DATA REPORTING

- o format of data submission
- o frequency of data reporting

VI. QUALITY ASSURANCE PROGRAM

- o calibration frequency
- o independent audit program
- o internal quality control procedures
- o data precision and accuracy calculation procedures

3. NETWORK DESIGN AND PROBE SITING CRITERIA

A source subject to PSD should proceed with designing a PSD monitoring network only after going through the procedure in Appendix A to determine if monitoring data will be required. To fulfill that requirement, a source may use representative air quality data which was discussed in Section 2.4 or monitor. This section presents guidance to be used if an applicant decides to monitor in lieu of using representative air quality data.

3.1 Network Design

The design of a network for criteria and noncriteria pollutants will be affected by many factors, such as topography, climatology, population, and existing emission sources. Therefore, the ultimate design of a network for PSD purposes must be decided on a case-by-case basis by the permit granting authority. Section 3.2 discusses the number and location of monitors for a PSD network. Additional guidance on the general siting of the monitors may be found in references 9-13 which discuss highest concentration stations, isolated point sources, effects of topography, etc. Probe siting criteria for the monitors are discussed in Section 3.3. The guidelines presented here should be followed to the maximum extent practical in developing the final PSD monitoring network.

3.2 Number and Location of Monitors

The number and location of monitoring sites will be determined on a case-by-case basis by the source owner or operator and reviewed by the permit granting authority. Consideration should be given to the effects of existing sources, terrain, meteorological conditions, existence of fugitive or reentrained dusts, averaging time for the pollutant, etc. Generally, the number of monitors will be higher where the expected spatial variability of the pollutant in the area(s) of study is higher.

3.2.1 Preconstruction Phase

Information obtained in the ambient air quality analysis in Appendix A will be used to assist in determining the number and location of monitors for the preconstruction phase. The air quality levels before construction were determined by modeling or in conjunction with monitoring data. The screening procedure (or more refined model) estimates were determined in Appendix A.

The source should first use the screening procedure or refined model estimates to determine the general location(s) for the maximum air quality concentrations from the proposed source or modification. Secondly, the source should determine by modeling techniques the general location(s) for the maximum air quality levels from existing sources. Thirdly, the modeled pollutant contribution of the proposed source or modification should be analyzed in conjunction with the modeled results for existing sources to determine the maximum impact area. Application of these models must be

consistent with EPA's "Guideline on Air Quality Models" [14]. This would provide sufficient information for the applicant to place a monitor at (a) the location(s) of the maximum concentration increase expected from the proposed source or modification, (b) the location(s) of the maximum air pollutant concentration from existing sources of emissions, and (c) the location(s) of the maximum impact area, i.e., where the maximum pollutant concentration would hypothetically occur based on the combination effect of existing sources and the proposed new source or modification. In some cases, two or more of these locations may coincide and thereby reduce the number of monitoring stations.

Monitoring should then be conducted in or as close to these areas as possible (also see discussion in Section 3.2.3). Generally, one to four sites would cover most situations in multisource settings. For remote areas in which the permit granting authority has determined that there are no significant existing sources, a minimum number of monitors would be needed, i.e., one or probably two at the most. For new sources, in these remote areas, as opposed to modifications, some concessions will be made on the locations of these monitors. Since the maximum impact from these new sources would be in remote areas, the monitors may be located, based on convenience or accessibility, near the proposed new source rather than near the maximum impact area since the existing air quality would be essentially the same in both areas. However, the maximum impact area is still the preferred location.

When industrial process fugitive particulate emissions are involved, the applicant should locate a monitor at the proposed source site (also see Section 3.2.3). If stack emissions are also involved, a downwind location should also be selected. For fugitive hydrocarbon emissions, the applicant should locate a monitor downwind of the source at the point of expected maximum ozone concentration contribution. This location will be found downwind during conditions that are most conducive to ozone formation, such as temperature above 20°C (68°F) and high solar radiation intensity. For hydrocarbon emissions from a stack, the applicant should also locate the monitor in the area of expected maximum ozone concentration. For both fugitive and stack emissions, the selection of areas of highest ozone concentrations will require wind speed and direction data for periods of photochemical activity. Monitoring for ozone will only be necessary during the seasons when high concentrations occur.

Since ozone is the result of a complex photochemical process, the rate of movement across an area of the air mass containing precursors should be considered. The distance from the proposed source to the monitor for an urban situation should be about equal to the distance traveled by the air moving for 5 to 7 hours at wind speeds occurring during periods of photochemical activity. In an urban situation, ozone formation over the initial few hours may be supressed by nitric oxide (NO) emissions. For a point source, the NO interactions may be minimal, and the travel time to the expected maximum ozone concentration may be 3 to 4 hours downwind. In general, the downwind distance for the maximum ozone site should generally

not be more than 15 to 20 miles from the source because a lower wind speed (2-3 miles per hour) with less dilution would be a more critical case. Additionally, the frequency that the wind would blow from the source over the site diminishes with increasing distances.

3.2.2 Postconstruction Phase

As discussed above for preconstruction monitoring, appropriate dispersion modeling techniques are used to estimate the location of the air quality impact of the new source or modification. Monitors should then be placed at (a) the expected area of the maximum concentration from the new source or modification, and (b) the maximum impact area(s), i.e., where the maximum pollutant concentration will occur based on the combined effect of existing sources and the new source or modification. It should be noted that locations for these monitors may be different from those sites for the preconstruction phase due to other new sources or modifications in the area since the preconstruction monitoring.

Generally, two or three sites would be sufficient for most situations in multisource areas. In remote areas where there are no significant existing sources, one or two sites would be sufficient. These sites would be placed at the locations indicated from the model results. The same concerns discussed in Section 3.2.1 regarding industrial process fugitive particulate emissions, fugitive hydrocarbon emissions, and ozone monitoring would also be applicable for the postconstruction phase.

3.2.3 Special Concerns for Location of Monitors

For the preconstruction and postconstruction phases, modeling is used to determine the general area where monitors would be located. Some of the modeled locations may be within the confines of the source's boundary. However, monitors should be placed in those locations satisfying the definition of ambient air. Ambient air is defined in 40 CFR 50.1(e) as "that portion of the atmosphere, external to buildings, to which the general public has access." Therefore, if the modeled locations are within an area excluded from ambient air, the monitors should be located downwind at the boundary of that area.

In some cases, it is simply not practical to place monitors at the indicated modeled locations. Some examples may include over open bodies of water, on rivers, swamps, cliffs, etc. The source and the permit granting authority should determine on a case-by-case basis alternative locations.

3.3 Probe Siting Criteria

The desire for comparability in monitoring data requires adherence to some consistent set of guidelines. Therefore, the probe siting criteria discussed below must be followed to the maximum extent possible to ensure uniform collection of air quality data that are comparable and compatible.

Before proceeding with the discussion of pollutant specific probe siting criteria, it is important to expand on the discussion in Section 3.2 of the location of monitors. In particular, reference is made to two monitoring objectives.

- Case 1: Locating monitors to determine the maximum concentration from the proposed source and/or existing sources.

- Case 2: Locating monitors to determine where the combined impact of the proposed source and existing sources would be expected to exhibit the highest concentrations.

For Case 1, the driving force for locating the siting area of the monitor as well as the specific location of the probe or instrument shelter is the objective of measuring the maximum impact from the proposed source. Two Case 1 examples are given. Consider the first situation in which a proposed source would be emitting pollutants from an elevated stack. Under these circumstances, sufficient mixing generally occurs during the transport of the emissions from the stack to the ground resulting in small vertical gradients near ground level, thus, a wide range of probe heights, 3-15 meters for gases and 2-15 meters for particulates is acceptable. For the same objective (maximum concentration from proposed source), consider the second example in which pollutants would be emitted from a ground level source. In this case, the concentration gradient near the ground can be large, thereby requiring a much tighter range of acceptable probe heights. For ground level sources emitting pollutants with steep vertical concentration gradients, efforts should be made to locate the inlet probe for gaseous pollutant monitors as close to 3 meters (a reasonable practical representation of the breathing zone) as possible and for particulate monitors using the hi-volume sampler 2 to 7 meters above ground level. The rationale for the 3 meters is that for gaseous pollutant measurements, the inlet probe can be adjusted for various heights even though the monitor is located in a building or trailer. On the contrary, the 2-3 meter height for the hi-volume sampler placement is not practical in certain areas. The 7 meter height allows for placement on a one story building and is reasonably close to representing the breathing zone.

Turn now to the second monitoring objective, Case 2, which is locating monitors to determine the maximum impact area taking into consideration the proposed source as well as existing sources. The critical element to keep in mind in locating a monitor to satisfy this objective is that the intent is to maximize the combined effect. Thus, in one circumstance, the existing source might contribute the largest impact. The importance of the above discussion to the topic of probe siting criteria is that in attempting to locate a monitor to achieve this objective, the placement of the probe or instrument shelter can vary depending upon which source is the predominant influence on the maximum impact area. As an extreme example, consider the situation where a proposed elevated source would emit CO into an urban area and have maximum combined CO impact coincident to an area adjacent to a heavily traveled traffic corridor. It is known that traffic along corridors

emit CO in fairly steep concentration gradients so the placement of the probe to measure the areas of highest CO concentration can vary significantly with probe height as well as distance from the corridor. In this example, the traffic corridor has the major influence on the combined impact and therefore controls the probe placement. As noted in the CO probe siting criteria in Section 3.3.3 as well as Appendix E of the May 10, 1979 Federal Register promulgation of the Ambient Air Monitoring Regulations [7] and revised and updated on March 19, 1986 [15], the required probe height in such microscale cases is given as 3 $\pm$ 1/2 meters while the distance of the probe from the roadway would be between 2 and 10 meters.

As another example, consider the case where the same proposed CO source would emit CO at elevated heights and have a combined maximum CO impact in an urban area that is only slightly affected by CO emissions from a roadway. The combined impact area in this case is far enough away from the two sources to provide adequate mixing and only small vertical concentration gradients at the impact area. In this case, the acceptable probe height would be in the range of 3-15 meters.

It is recognized that there may be other situations occurring which prevent the probe siting criteria from being followed. If so, the differences must be thoroughly documented. This documentation should minimize future questions about the data.

The desire for comparability in monitoring data requires adherence to some consistent set of guidelines. Therefore, the probe siting criteria discussed below must be followed to the maximum extent possible to ensure uniform collection of air quality data that are comparable and compatible. To achieve this goal, the specific siting criteria that are prefaced with a "must" are defined as a requirement and exceptions must be approved by the permit granting authority. However, siting criteria that are prefaced with a "should" are defined as a goal to meet for consistency, but are not a requirement.

3.3.1 Total Suspended Particulates (TSP)

Section 3.3.1 is applicable only for the following cases. PSD applications submitted not later than 6 months after the effective date of the 1987 PSD amendments would use this siting criteria when collecting TSP monitoring data. Also, representative air quality data for TSP collected not later than 6 months after the effective date of the 1987 PSD amendments would use this siting criteria.

3.3.1.1 Vertical Placement - The most desirable height for a TSP monitor is near the breathing zone. However, practical considerations such as prevention of vandalism, security, accessibility, availability of electricity, etc., generally require that the sampler be elevated. Therefore, a range of acceptable heights needs to be used. In addition, the type of source, i.e., elevated or ground level, predominantly influencing the area of impact must be considered when locating the monitor. For purposes of

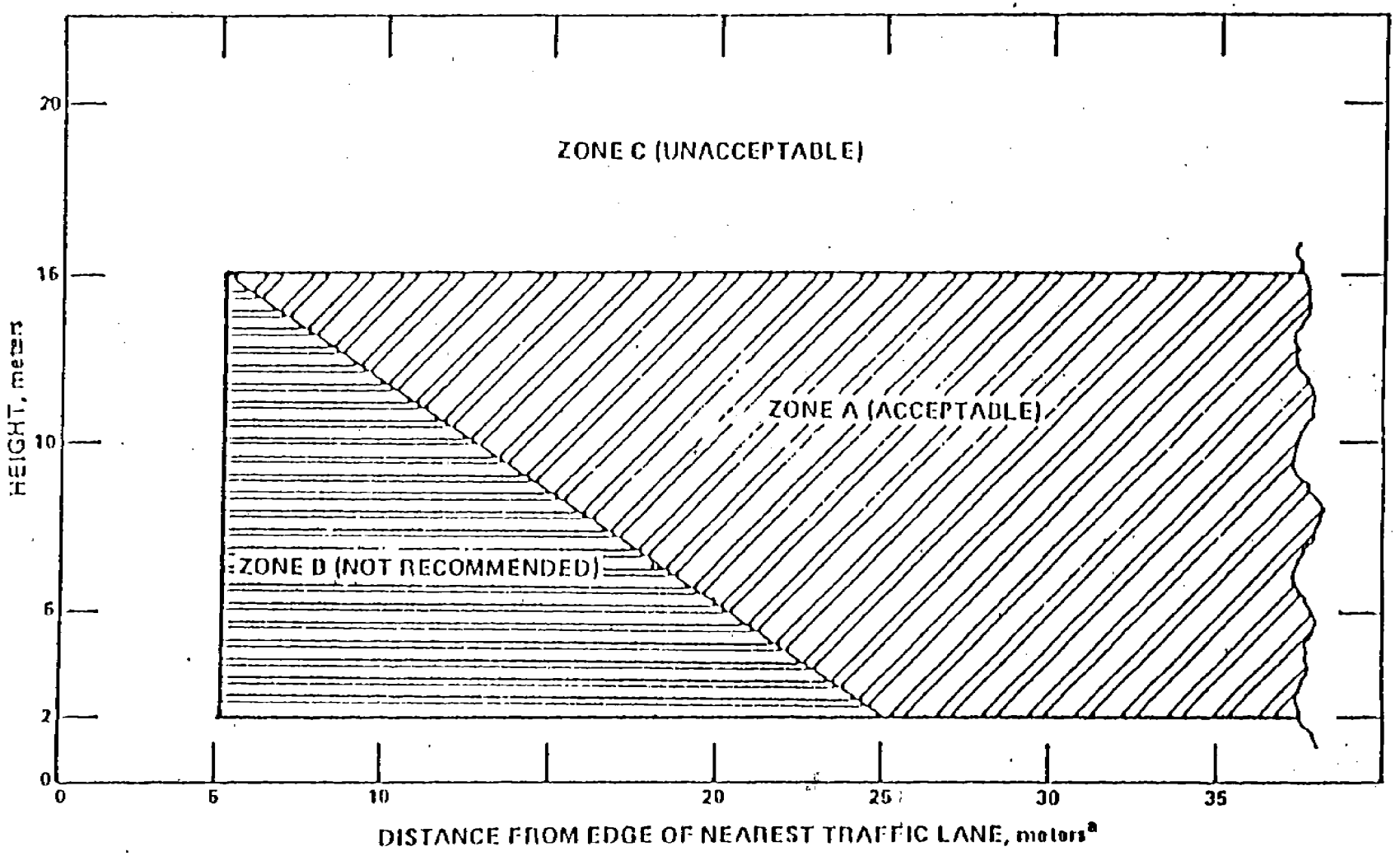
determining elevated source impact, the sampler air intake must be located 2-15 meters above ground level. The lower limit was based on a compromise between ease of servicing the sampler and the desire to avoid reentrainment from dusty surfaces. The upper limit represents a compromise between the desire to have measurements which are most representative of population exposures, and the considerations noted earlier. For ground level sources with steep vertical concentration gradients, the air intake must be as close to the breathing zone as practical.

3.3.1.2 Spacing from Obstructions - If the sampler is located on a roof or other structure, then there must be a minimum of 2 meters separation from walls, parapets, penthouses, etc. Furthermore, no furnace or incineration flues should be nearby. The separation distance from flues is dependent on the height of the flues, type of waste or fuel burned, and quality of the fuel (ash content). For example, if the emissions from the chimney are the result of natural gas combustion, no special precautions are necessary except for the avoidance of obstructions, i.e., at least 2 meters separation. On the other hand, if fuel oil, coal, or solid waste is burned and the stack is sufficiently short so that the plume could reasonably be expected to impact on the sampler intake a significant part of the time, other buildings/locations in the area that are free from these types of sources should be considered for sampling. Trees provide surfaces for particulate deposition and also restrict airflow. Therefore, the sampler should be placed at least 20 meters from the dripline of trees and must be 10 meters from the dripline when trees act as an obstruction [15].

Obstacles such as buildings must also be avoided so that the distance between obstacles and the sampler is at least twice the height that the obstacle protrudes above the sampler. In addition, there must be unrestricted airflow in an arc of at least 270° around the sampler, and the predominant direction for the season of greatest pollutant concentration potential must be included in the 270° arc.

3.3.1.3 Spacing from Roads - A number of studies [16-23] support the conclusion that particulate concentrations decrease with increasing height of the monitor and distance from the road. Quite high concentrations have been reported at monitors located at a low elevation close to heavily traveled roads. Moreover, monitors located close to streets are within the concentrated plume of particulate matter emitted and generated by vehicle traffic. Therefore, ambient monitors for TSP should be located beyond the concentrated particulate plume generated by traffic, and not so close that the heavier reentrained roadway particles totally dominate the measured ambient concentration.

An analysis of various monitoring studies [24] shows that a linear relationship between sampler height and distance from roadways defines a zone where the plume generated by traffic greater than approximately 3,000 vehicles per day is diminished. Figure 1 illustrates this relationship by showing two zones where TSP monitors could be located. Zone A represents locations which are recommended and Zone B represents locations which



[a]APPLIES WHERE ADT >3 000

Figure 1. Acceptable zone for siting TSP monitors

should be avoided in order to minimize undesirable roadway influences. Roads with lower traffic (less than approximately 3,000 vehicles per day) are generally not considered to be a major source or vehicularrelated pollutants, and so as noted in Figure 1 do not preclude the use of monitors in Zone B for those situations. However, note that for those cases where the traffic is less than approximately 3,000 vehicles per day, the monitor must be located greater than 5 meters from the edge of the nearest traffic lane and 2 to 15 meters above ground level.

In the case of elevated roadways where the monitor must be placed below the level of the roadway, the monitor should be located no closer than approximately 25 meters from the edge of the nearest traffic lane. This separation distance applies for those situations where the road is elevated greater than 5 meters above the ground level, and applies to all traffic volumes.

3.3.1.4 Other Considerations - Stations should not be located in an unpaved area unless there is vegetative ground cover year round so that the impact of reentrained or fugitive dusts will be kept to a minimum. Additional information on TSP probe siting may be found in reference 9.

3.3.2 PM_{10}

3.3.2.1. Vertical Placement - Although there are limited studies on the PM_{10} concentration gradients around roadways or other ground level sources, references 16, 17, 19, 25, and 26 show a distinct variation in the distribution of TSP and Pb levels near roadways. TSP, which is greatly affected by gravity, has large concentration gradients, both horizontal and vertical, immediately adjacent to roads. Pb, being predominantly submicron in size, behaves more like a gas and does not exhibit steep vertical and horizontal gradients as does TSP. PM_{10}, being intermediate in size between these two extremes exhibits dispersion properties of both gas and settleable particulates and does show vertical and horizontal gradients [27]. Similar to monitoring for other pollutants, optimal placement of the sampler inlet for PM_{10} monitoring should be at breathing height level. However, practical factors such as prevention of vandalism, security, and safety precautions must also be considered when siting a PM_{10} monitor. Given these considerations, the sampler inlet for ground level source monitoring must be 2-7 meters above ground level. For PM_{10} samplers, the acceptable range for monitoring emissions from elevated sources is 2-15 meters above ground level.

3.3.2.2 Spacing from Obstructions - If the sampler is located on a roof or other structure, then there must be a minimum of 2 meters separation from walls, parapets, penthouses, etc. No furnace or incineration flues should be nearby. This separation distance from flues is dependent on the height of the flues, type of waste or fuel burned, and quality of the fuel (ash content). In the case of emissions from a chimney resulting from natural gas combustion, the sampler should be placed, as a precautionary measure, at least 5 meters from the chimney.

On the other hand, if fuel oil, coal, or solid waste is burned and the stack is sufficiently short so that the plume could reasonably be expected to impact on the sampler intake a significant part of the time, other buildings/locations in the area that are free from these types of sources should be considered for sampling. Trees provide surfaces for particulate deposition and also restrict airflow. Therefore, the sampler should be placed at least 20 meters from the dripline of trees and must be 10 meters from the dripline when trees act as an obstruction [15].

The sampler must also be located away from obstacles such as buildings, so that the distance between obstacles and the sampler is at least twice the height that the obstacle protrudes above the sampler. There must also be unrestricted airflow in an arc of at least 270° around the sampler, and the predominant wind direction for the season of greatest pollutant concentration potential must be included in the 270° arc.

3.3.2.3 Spacing from Roads - For these situations where the emissions from a proposed source would impact close to a roadway, the air intake for the monitor must be located between 5-15 meters from the edge of the nearest traffic lane. Monitors located in this area would thus measure the combined impact from the proposed source and the roadway. The sampler air intake must be 2-7 meters above ground level.

3.3.2.4 Other Considerations - Stations should not be located in an unpaved area unless there is vegetative ground cover year round so that the impact of reentrained or fugitive dusts will be kept to a minimum. Additional information on PM_{10} siting may be found in reference 28.

3.3.3 Sulfur Dioxide (SO_2)

3.3.3.1. Horizontal and Vertical Probe Placement - As with TSP monitoring, the most desirable height for an SO_2 inlet probe is near the breathing height. Various factors enumerated before may require that the inlet probe be elevated. consideration must also be given to the type of source predominantly influencing the impact area. For elevated sources, the inlet probe must be located 3 to 15 meters above ground level. For ground level sources, locate as close to the breathing zone as possible. If the inlet probe is located on the side of the building, then it should be located on the windward side of the building relative to the prevailing winter wind direction. The inlet probe must also be located more than 1 meter vertically or horizontally away from any supporting structure and also away from dirty, dusty areas.

3.3.3.2 Spacing from Obstructions - No furnace or incineration flues, or other minor sources of SO_2 should be nearby. The separation distance is dependent on the height of the flues, type of waste or fuel burned, and the quality of the fuel (sulfur content). If the inlet probe is located on a roof or other structure, it must be at least 1 meter from walls, parapets, penthouses, etc.

The inlet probe should be placed at least 20 meters from the dripline of trees and must be 10 meters from the dripline when trees act as an obstruction [15]. Additionally, the probe must be located away from obstacles and buildings. The distance between the obstacles and the inlet probe must be at least twice the height that the obstacle protrudes above the inlet probe. Airflow must also be unrestricted in an arc of at least 270° around the inlet probe, and the predominant direction for the season of greatest pollutant concentration potential must be included in the 270° arc. If the probe is located on the side of a building, 180° clearance is required. Additional information on SO_2 probe siting criteria may be found in reference 10.

3.3.4 Carbon Monoxide (CO)

3.3.4.1 Horizontal and Vertical Probe Placement - Because of the importance of measuring population exposure to CO concentrations, optimum CO sampling should be done at average breathing heights. However, practical factors require that the inlet probe be higher. In general, for CO emitted at elevated heights, the inlet probe for CO monitoring should be 3-15 meters above ground level. For those situations where the emissions from a proposed source would impact a street canyon or corridor type area in an urban area, and the area is prodominantly influenced by the traffic from the street canyon or traffic corridor, the inlet probe should be positioned 3 $\pm$ 1/2 meters above ground level which coincides with the vertical probe placement criteria for a street canyon/corridor type site [7]. The criteria is more stringent than the 3 to 15 meter range specified earlier because CO concentration gradients resulting from motor vehicles traveling along street canyon or corridors are rather steep and show wide variations in CO levels at different heights. The 3 meter height is a compromise between breathing height representation and such factors as the prevention of obstructions to pedestrians, vandalism, etc.

In addition to the vertical probe criteria, the inlet probe must also be located more than 1 meter in the vertical or horizontal direction from any supporting structure.

3.3.4.2 Spacing from Obstructions - Airflow must also be unrestricted in an arc of at least 270° around the inlet probe, and the predominant direction for the season of greatest pollutant concentration potential must be included in the 270° arc. If the probe is located on the side of a building, 180° clearance is required [7, 15]. Additionally, trees should not be located between the major sources of CO and the sampler. The sampler must be at least 10 meters form the dripline of a tree which is between the sampler and the source if the tree extends at least 5 meters above the sampler [15].

3.3.4.3 Spacing from Roads - For those situations discussed above where the emissions from a proposed source would impact a street canyon/corridor type area, the inlet probe must be located at least 10 meters from an intersection and preferably at a midblock location. The inlet probe must also be placed 2-10 meters from the edge of the nearest traffic lane.

Also no trees or shrubs should be located between the sampling inlet probe and the road [15]. Additional information on CO probe siting may be found in reference 11.

3.3.5 Ozone (O_3)

3.3.5.1 Vertical and Horizontal Probe Placement - The inlet probe for ozone monitors should be as close as possible to the breathing zone. The complicating factors discussed previously, however, require that the probe be elevated. The height of the inlet probe must be located 3 to 15 meters above ground level. The probe must also be located more than 1 meter vertically or horizontally away from any supporting structure.

3.3.5.2 Spacing from Obstructions - The probe must be located away from obstacles and buildings such that the distance between the obstacles and the inlet probe is at least twice the height that the obstacle protrudes above the sampler. The probe should also be located at least 20 meters from the dripline of trees. Since the scavenging effect of trees is greater for ozone than for some of the other pollutants, strong consideration should be used in locating the inlet probe to avoid this effect. Therefore, the sampler must be at least 10 meters from the dripline of trees that are located between the source of the ozone precursors and the sampler along the predominant summer daytime wind direction [15]. Airflow must be unrestricted in an arc of at least 270° around the inlet probe, and the predominant direction for the season of greatest pollutant concentration potential must be included in the 270° arc. If the probe is located on the side of a building, 180° clearance is required.

3.3.5.3 Spacing from Roads - It is important in the probe siting process to minimize destructive interferences from sources of nitric oxide (NO) since NO readily reacts with ozone. Regarding NO from motor vehicles, Table 2 provides the required minimum separation distances between roadways and ozone monitoring stations. These distances were based on recalculations using the methodology in reference 12 and validated using more recent ambient data collected near a major roadway. The minimum separation distance must also be maintained between an ozone station and other similar volumes of automotive traffic, such as parking lots. Additional information on ozone probe siting criteria may be found in reference 12.

Table 2. MINIMUM SEPARATION DISTANCE BETWEEN OZONE MONITORS AND ROADWAYS (EDGE OF NEAREST TRAFFIC LANE)

Roadway Average Daily Traffic, Vehicles Per Day	Minimum Separation Distance Between Roadways and Monitors, Meters
≤ 10,000	≥ 10[a]
15,000	20
20,000	30
40,000	50
70,000	100
≥110,000	≥250

[a]Distances should be interpolated based on traffic flow.

3.3.6 Nitrogen Dioxide (NO_2)

3.3.6.1 Vertical and Horizontal Probe Placement - As discussed for previous pollutants, the acceptable ranges for a monitor/probe inlet for monitoring NO_2 emissions in an area principally influenced by an elevated source is 3-15 meters. For areas influenced primarily by a ground level source, the height should be as close to 3 meters as possible. Regarding the distance of the probe from the supporting structure, a vertical or horizontal distance of 1 meter must be maintained.

3.3.6.2 Spacing from Obstructions - Buildings, trees, and other obstacles can serve as scavengers of NO_2. In order to avoid this kind of interference, the station must be located well away from such obstacles so that the distance between obstacles and the inlet probe is at least twice the height that the obstacle protrudes above the probe. Also, a probe inlet along a vertical wall is undesirable because air moving along that wall may be subject to possible removal mechanisms. Similarly, the inlet probe should also be at least 20 meters from the dripline of trees and must be at least 10 meters from the dripline of trees which protrude above the height of the probe by 5 of more meters [15]. There must be unrestricted airflow in an arc of at least 270° around the inlet probe, and the predominant direction for the season of greatest pollutant concentration potential must be included in the 270° arc. If the probe is located on the side of the building, 180° clearance is required. Additional information on NO_2 probe siting criteria may be found in reference 12.

3.3.7 Lead (Pb)

3.3.7.1 Vertical Placement - Breathing height is the most desirable location for the vertical placement of the Pb monitor. However, practical factors previously mentioned require that the monitor be elevated. In elevating the sampler, consideration must be given to ground level emissions (whether they be stationary or mobile sources) with steep vertical concentration gradients. Placing the shelter too high could result in measured values

significantly lower than the level breathed by the general public. Accordingly, the sampler for ground level source monitoring must be located 2 to 7 meters above ground level. In contrast, samplers to monitor for elevated sources, as noted in previous discussion, are allowed a wider range of heights for locating the sampler/inlet probe. For Pb samplers, the acceptable range for monitoring emissions from elevated sources is 2-15 meters above ground level.

3.3.7.2 Spacing from Obstructions - A minimum of 2 meters of separation from walls, parapets, and penthouses is required for samplers located on a roof or other structure. No furnace or incineration flues should be nearby. The height of the flues and the type, quality, and quantity of waste or fuel burned determine the separation distances from flues. For example, if the emissions from the chimney have a high lead content and there is a high probability that the plume would impact on the sampler during most of the sampling period, then other buildings/locations in the area that are free from the described sources should be chosen for the monitoring site. The sampler should be placed at least 20 meters from the dripline of trees and must be at least 10 meters from the dripline of trees when the tree(s) could be classified as an obstruction [15], since trees absorb particles as well as restrict airflow.

The sampler must be located away from obstacles such as buildings, so that the distance between obstacles and the sampler is at least twice the height that the obstacle protrudes above the sampler. There must also be unrestricted airflow in an arc of at least 270° around the sampler, and the predominant direction for the season of greatest pollution concentration potential must be included in the 270° arc.

3.3.7.3 Spacing from Roads - For those situations discussed in Section 3.3.7.1 where the emissions from a proposed source would impact close to a major roadway (greater than approximately 30,000 ADT), the air intake for the monitor must be located within 15-30 meters from the edge of the nearest traffic lane. Monitors located in this area would thus measure the combined impact from the proposed source and the roadway. The sampler air intake must be 2 to 7 meters above ground level.

3.3.7.4 Other Considerations - Stations should not be located in an unpaved area unless there is vegetative ground cover year round so that the impact of reentrained or fugitive dusts will be kept to a minimum. Additional information on Pb siting criteria may be found in reference 13.

3.3.8 Noncriteria Pollutants

3.3.8.1 Vertical Placement - Similar to the discussion on criteria pollutants, the most desirable height for monitors/inlet probes for noncriteria pollutants is near the breathing zone. Again, practical factors require that the monitor/ inlet probe be elevated. Furthermore, consideration must be given to the type of source, i.e., elevated, ground level, stationary, or mobile. As the case may be, for noncriteria particulate pollutant monitors, the

following monitor/inlet probe ranges are acceptable: for impact areas predominantly influenced by elevated sources, 2-15 meters; for ground level sources 2 to 7 meters. Regarding noncriteria gaseous pollutants, acceptable heights are as follows: areas impacted primarily by elevated sources, 3-15 meters; areas affected principally by ground level sources, as close to 3 meters as possible.

3.3.8.2 Spacing from Obstructions - If the sampler/inlet probe is located on a roof or other structure, then there must be a minimum of 2 meters separation from walls, parapets, penthouses, etc. No furnace or incineration flues should be nearby. This separation distance from flues is dependent on the height of the flues, type of waste or fuel burned, and quality of the fuel. For example, if the emissions from the chimney contain a high concentraton of the noncriteria pollutant that is being measured and there is a high probability that the plume would impact the sampler/inlet probe during most of the sampling period, then other buildings/locations in the area that are free from the described sources should be chosen for the monitoring site. The sampler/inlet probe should also be placed at least 20 meters from the dripline of trees and must be at least 10 meters from the dripline of tree(s) that could be classified as an obstruction [15].

The sampler/inlet probe must be located away from obstacles and buildings such that the distance between the obstacles and the sampler/inlet probe is at least twice the height that the obstacle protrudes above the sampler/inlet probe. Airflow must be unrestricted in an arc of at least 270° around the sampler/inlet probe, and the predominant direction for the season of greatest pollutant concentration potential must be included in the 270° arc. If the inlet probe is located on the side of a building, 180° clearance is required.

3.3.8.3 Other Considerations - Stations for measuring particulate noncriteria pollutants should not be located in an unpaved area unless there is vegetative ground cover year round so that the impact of reentrained or fugitive dusts will be kept to a minimum.

3.4 Probe Material and Pollutant Sample Residence Time

For reactive gases, special probe material must be used. Studies [29-33] have been conducted to determine the suitability of materials such as polypropylene, polyethylene, polyvinylchloride, tygon, aluminum, brass, stainless steel, copper, pyrex glass, and teflon for use as intake sampling lines. Of the above materials, only pyrex glass and teflon have been found to be acceptable for use as intake sampling lines for all the reactive gaseous pollutants. Furthermore, EPA [34] has specified borosilicate glass or FEP teflon as the only acceptable probe materials for delivering test atmospheres in the determination of reference or equivalent methods. Therefore, borosilicate glass, FEP teflon, or their equivalent must be used for inlet probes.

No matter how unreactive the sampling probe material is initially, after a period of use, reactive particulate matter is deposited on the probe walls. Therefore, the time it takes the gas to transfer from the probe inlet to the sampling device is also critical. Ozone in the presence of NO will show significant losses even in the most inert probe material when the residence time exceeds 20 seconds [35]. Other studies [36-37] indicate that a 10-second or less residence time is easily achievable. Therefore, sampling probes for reactive gas monitors must have a sampler residence time less than 20 seconds.

3.5 Summary of Probe Siting Requirements

Table 3 presents a summary of the requirements for probe siting criteria with respect to distances and heights. These criteria are specified for consistency between pollutants and to allow the use of a single manifold for monitoring more than one pollutant at a site.

TABLE 3. SUMMARY OF PROBE SITING CRITERIA

Pollutant	Height Above Ground, Meters[a]	Distance from Supporting Structure, Meters		Other Spacing Criteria
		Vertical	Horizontal[b]	
TSP	2 - 15	--	>2	1. Should be >20 meters from the dripline and must be 10 meters from the dripline when the tree(s) act as an obstruction. 2. Distance from sampler to obstacle, such as buildings, must be at least twice the height the obstacle protrudes above the sampler. 3. Must have unrestricted airflow 270° arc around the sampler. 4. No furnace or incineration flues should be nearby.[c] 5. Must have minimum spacing from roads. This varies with height of monitor (see Figure 1).
PM_{10} (impact near major roadway and/or ground level sources)	2 - 7	--	>2	1. Should be >20 meters from the dripline and must be 10 meters from the dripline when the tree(s) act as an obstruction. 2. Distance from sampler to obstacle, such as buildings, must be at least twice the height the obstacle protrudes above the sampler. 3. Must have unrestricted airflow 270° arc around the sampler. 4. No furnace or incineration flues which emit particulate matter should be nearby.[c] 5. Must be 5-15 meters from roads.

TABLE 3. SUMMARY OF PROBE SITING CRITERIA
(continued)

Pollutant	Height Above Ground, Meters[a]	Distance from Supporting Structure, Meters		Other Spacing Criteria
		Vertical	Horizontal[b]	
PM_{10}	2 - 15	--	>2	1. Should be >20 meters from the dripline and must be 10 meters from the dripline when the tree(s) act as an obstruction. 2. Distance from sampler to obstacle, such as buildings, must be at least twice the height the obstacle protrudes above the sampler. 3. Must have unrestricted airflow 270° arc around the sampler. 4. No furnace or incineration flues which emit particulate matter should be nearby.[3]
SO_2	3 - 15	>1	>1	1. Should be >20 meters from the dripline and must be 10 meters from the dripline when the tree(s) act as an obstruction. 2. Distance from inlet probe to obstacle, such as buildings, must be at least twice the height the obstacle protrudes above the inlet probe. 3. Must have unrestricted airflow 270° arc around the inlet probe, or 180° if probe is on the side of a building. 4. No furnace or incineration flues should be nearby.[c]

TABLE 3. SUMMARY OF PROBE SITING CRITERIA
(continued)

Pollutant	Height Above Ground, Meters[a]	Distance from Supporting Structure, Meters		Other Spacing Criteria
		Vertical	Horizontal[b]	
CO (street/canyon)	3 ± 1/2	>1	>1	1. Must be >10 meters from intersection and should be at a midblock location. 2. Must be 2-10 meters from edge of nearest traffic lane. 3. Must have unrestricted airflow 180° around the inlet probe.
CO (non-street canyon/corridor)	3 - 15	>1	>1	1. Must have unrestricted airflow 270° around the inlet probe, or 180° if probe is on the side of a building.
O_3	3 - 15	>1	>1	1. Should be >20 meters from the dripline and must be 10 meters from the dripline when the tree(s) act as an obstruction. 2. Distance from inlet probe to obstacle, such as buildings, must be at least twice the height the obstacle protrudes above the inlet probe. 3. Must have unrestricted airflow 270° arc around the inlet probe, or 180° if probe is on the side of a building. 4. Spacing from roads varies with traffic (see Table 2).

TABLE 3. SUMMARY OF PROBE SITING CRITERIA
(continued)

Pollutant	Height Above Ground, Meters[a]	Distance from Supporting Structure, Meters		Other Spacing Criteria
		Vertical	Horizontal[b]	
NO_2	3 - 15	>1	>1	1. Should be >20 meters from the dripline and must be 10 meters from the dripline when the tree(s) act as an obstruction. 2. Distance from inlet probe to obstacle, such as buildings, must be at least twice the height the obstacle protrudes above the inlet probe. 3. Must have unrestricted airflow 270° arc around the inlet probe, or 180° if probe is on the side of a building.
Pb (impact near major roadway and/or ground level sources)	2 - 7	--	>2	1. Should be >20 meters from the dripline and must be 10 meters from the dripline when the tree(s) act as an obstruction. 2. Distance from sampler to obstacle, such as buildings, must be at least twice the height the obstacle protrudes above the sampler. 3. Must have unrestricted airflow 270° arc around the sampler. 4. No furnace or incineration flues which emit lead should be nearby.[c] 5. Must be 15-30 meters from major roadways.

TABLE 3. SUMMARY OF PROBE SITING CRITERIA
(continued)

Pollutant	Height Above Ground, Meters[a]	Distance from Supporting Structure, Meters		Other Spacing Criteria
		Vertical	Horizontal[b]	
Pb	2 - 15	--	>2	1. Should be >20 meters from the dripline and must be 10 meters from the dripline when the tree(s) act as an obstruction. 2. Distance from sampler to obstacle, such as buildings, must be at least twice the height the obstacle protrudes above the sampler. 3. Must have unrestricted airflow 270° arc around the sampler. 4. No furnace or incineration flues which emit lead should be nearby.[c]
Particulate Noncriteria Pollutants	2 - 7 for ground level sources; 2 - 15 for elevated sources	--	>2	1. Should be >20 meters from the dripline and must be 10 meters from the dripline when the tree(s) act as an obstruction. 2. Distance from sampler to obstacle, such as buildings, must be at least twice the height the obstacle protrudes above the sampler. 3. Must have unrestricted airflow 270° arc around the sampler. 4. No furnace or incineration flues which emit the noncriteria pollutant should be nearby.[c]

TABLE 3. SUMMARY OF PROBE SITING CRITERIA
(continued)

Pollutant	Height Above Ground, Meters[a]	Distance from Supporting Structure, Meters		Other Spacing Criteria
		Vertical	Horizontal[b]	
Gaseous Noncriteria Pollutants	3 - 15	>1	>1	1. Should be >20 meters from the dripline and must be 10 meters from the dripline when the tree(s) act as an obstruction. 2. Distance from inlet probe to obstacle, such as buildings, must be at least twice the height obstacle protrudes above the inlet probe. 3. Must have unrestricted airflow 270° arc around the inlet probe, or 180° if the probe is on the side of a building. 4. No furnace or incineration flues which emit the noncriteria pollutant should be nearby.[b]

[a]For ground level sources, monitors/inlet probes should be placed as close to the breathing zone as possible.

[b]When probe is located on rooftop, this separation distance is in reference to walls, parapets, or penthouses located on the roof.

[c]Distance is dependent on height of furnace or incineration flue, type of fuel or waste burned, and quality of fuel. This is to avoid undue influences from minor pollutant sources.

4. QUALITY ASSURANCE FOR AIR QUALITY DATA

On May 10, 1979, EPA promulgated quality assurance requirements for PSD monitoring for SO_2, NO_2, O_3, CO, and TSP. These quality assurance requirements were revised and updated on March 19, 1986 [15]. These quality assurance requirements are Appendix B of 40 CFR 58 (reference 7). Section 4.1 describes minimum quality assurance requirements for PSD monitoring for all criteria air pollutants (SO_2, NO_2, O_3, CO, TSP, Pb and PM_{10}). Monitoring organizations are required to meet quality assurance requirements of Appendix B at the time the station is put into operation.

Currently, quality assurance for PSD monitoring for noncriteria air pollutants are EPA recommendations only. EPA promulgated requirements are not available for noncriteria air pollutants. Section 4.2 describes minimum quality assurance recommendations for noncriteria air pollutants.

4.1 Quality Assurance for Criteria Air Pollutants

4.1.1 General Information

The following specifies the minimum quality assurance requirements of an organization operating a network of PSD stations. These requirements are regarded as the minimum necessary for the control and assessment of the quality of the PSD ambient air monitoring data submitted to EPA. Organizations are encouraged to develop and implement quality assurance programs more extensive than the minimum required or to continue such programs where they already exist.

Quality assurance consists of two distinct and equally important functions. One function is the assessment of the quality of the monitoring data by estimating their precision and accuracy. The other function is the control, and improvement, of the quality of the monitoring data by implementation of quality control policies, procedures, and corrective actions. These two functions form a control loop; when the assessment function indicates that the data quality is inadequate, the control effort must be increased until the data quality is acceptable.

In order to provide uniformity in the assessment and reporting of data quality, the assessment procedures are specified explicitly in Sections 4.1.3, 4.1.4, 4.1.5 and 4.1.6.

In contrast, the control and corrective action function encompasses a variety of policies, procedures, specifications, standards, and corrective measures which have varying effects on the resulting data quality. The selection and degree of specific control measures and corrective actions used depend on a number of factors such as the monitoring methods and equipment used, field and laboratory conditions, the objectives of the monitoring, the level of data quality needed, the expertise of personnel, the cost of control procedures, pollutant concentration levels, etc.

Accordingly, quality control requirements are specified in general terms, in Section 4.1.2 to allow each organization to develop a quality control system which is most effective for its own circumstances.

For purposes here, "organization" is defined as a source owner/operator, a government agency, or their contractor which operates an ambient air pollution monitoring network for PSD purposes.

4.1.2 Quality Control Requirements

4.1.2.1 Organizational Requirements - Each organization must develop and implement a quality control program consisting of policies, procedures, specifications, standards and documentation necessary to:

(a) meet the monitoring objectives and quality assurance requirements of the permit granting authority

(b) minimize loss of air quality data due to malfunctions or out-of-control conditions,

The quality control program must be described in detail, suitably documented, and approved by the permit granting authority.

4.1.2.2 Primary Guidance - Primary guidance for developing the quality control program is contained in references 38 and 39, which also contain many suggested procedures, checks, and control specifications. Section 2.0.9 of reference 39 describes the specific guidance for the development of a quality control program for PSD automated analyzers and manual methods. Many specific quality control checks and specifications for manual methods are included in the respective reference methods described in 40 CFR 50, or in the respective equivalent method descriptions available from EPA (see Section 2.6). Similarly, quality control procedures related to specifically designated reference and equivalent analyzers are contained in their respective operation and instruction manuals. This guidance, and any other pertinent information from appropriate sources, should be used by organizations in developing their quality control programs.

As a minimum each quality control program must have operational procedures for each of the following activities:

(a) selection of methods, analyzers, or samplers,
(b) installation of equipment,
(c) calibration,
(d) zero and span checks and adjustments of automated analyzers,
(e) control checks and their frequency,
(f) control limits for zero, span and other control checks, and respective corrective actions when such limits are surpassed,
(g) calibration and zero/span checks for multiple range analyzers
(h) preventive and remedial maintenance
(i) recording and validating data
(j) documentation of quality control information.

As previously mentioned, specific guidance for each activity listed above that must be a part of an organization's quality control program is described in Section 2.0.9 of reference 39.

4.1.2.3 Pollutant Standards - Gaseous standards (permeation tubes, permeation devices or cylinders of compressed gas) used to obtain test concentrations for CO, SO_2, and NO_2 must be working standards certified by comparison to a National Bureau of Standards (NBS) gaseous Standard Reference Material (SRM). A traceability protocol for certifying a working standard by direct comparison to an NBS SRM is given in reference 40. Direct use of an NBS SRM as a working standard is not prohibited but is discouraged because of the limited supply and expense of NBS SRM's. When available, gas manufacturers' cylinder gases Certified Reference Materials "CRM" may be substituted for NBS SRM cylinder gases in establishing traceability.

Test concentrations for ozone must be obtained in accordance with the UV photometric calibration procedure specified in Appendix D of 40 CFR 50, or by means of an ozone transfer standard which has been certified. Consult reference 41 for guidance on ozone transfer standards.

Flow measurements must be made by a flow measuring instrument which is traceable to an authoritative volume or other standard.

4.1.2.4 Performance and System Audit Programs - The organization operating a PSD monitoring network must participate in EPA's national performance audit program. The permit granting authority, or EPA, may conduct system audits of the ambient air monitoring programs of organizations operating PSD networks. See Section 1.4.16 of reference 38 and Sections 2.0.11 and 2.0.12 of reference 39 for additional information about these programs. Organizations should contact either the appropriate EPA Regional Quality Control Coordinator or the Quality Assurance Division, EMSL/RTP, at the address given in reference 40 for instructions for participation.

4.1.3 Data Quality Assessment Requirements

4.1.3.1 Precision of Automated Methods - A one-point precision check must be carried out at least once every two weeks on each automated analyzer used to measure SO_2, NO_2, O_3, and CO. The precision check is made by challenging the analyzer with a precision check gas of known concentration between 0.008 and 0.10 ppm for SO_2, NO_2, and O_3 analyzers, and between 8 and 10 ppm for CO analyzers. The standards from which precision check test concentrations are obtained must meet the specifications of section 4.1.2.3. Except for certain CO analyzers described below, analyzers must operate in their normal sampling mode during the precision check, and the test atmosphere must pass through all filters, scrubbers, conditioners, and other components used during normal ambient sampling and as much of the ambient air inlet system as is practicable. If permitted by the associated operation or instruction manual, a CO analyzer may be temporarily modified during the precision check to reduce vent or purge flows, or the test atmosphere may

enter the analyzer at a point other than the normal sample inlet, provided that the analyzer's response is not likely to be altered by these deviations from the normal operational mode.

If a precision check is made in conjunction with zero/span adjustment, it must be made prior to such zero and span adjustments. The difference between the actual concentration of the precision check gas and the concentration indicated by the analyzer is used to assess the precision of the monitoring data as described in Section 4.1.4.1. Report data only from automated analyzers that are approved for use in the PSD network.

4.1.3.2 Accuracy of Automated Methods - Each sampling quarter audit each analyzer that monitors for SO_2, NO_2, O_3, or CO at least once. The audit is made by challenging the analyzer with at least one audit gas of known concentration from each of the following ranges which fall within the measurement range of the analyzer being audited:

Audit Point	Concentration Range, ppm		
	SO_2, O_3	NO_2	CO
1	0.03 to 0.08	0.03 to 0.08	3 to 8
2	0.15 to 0.20	0.15 to 0.20	15 to 20
3	0.35 to 0.45	0.35 to 0.45	35 to 45
4	0.80 to 0.90		80 to 90

The standards from which audit gas test concentrations are obtained must meet the specifications of Section 4.1.2.3. Working and transfer standards and equipment used for auditing must be different from the standards and equipment used for calibration and spanning. The auditing standards and calibration standards may be referenced to the same NBS SRM or primary UV photometer. The auditor must not be the operator/analyst who conducts the routine monitoring, calibration, and analysis.

The audit shall be carried out by allowing the analyzer to analyze an audit test atmosphere in the same manner as described for precision checks in Section 4.1.3.1. The exception given in Section 4.1.3.1 for certain CO analyzers does not apply for audits.

The difference between the actual concentration of the audit test gas and the concentration indicated by the analyzer is used to assess the accuracy of the monitoring data as described in Section 4.1.4.2. Report data only from automated analyzers that are approved for use in the PSD network.

4.1.3.3 Precision of Manual Methods - (a) TSP and PM_{10} Methods. For a given organization's monitoring network, one sampling site must have collocated samplers. A site with the highest expected 24-hour pollutant concentration must be selected. The two samplers must be within 4 meters of each other but at least 2 meters apart to preclude airflow interference. Calibration, sampling, and analysis must be the same for both collocated samplers as well as for all other samplers in the network. The collocated samplers must be operated as a minimum every third day when continuous sampling is used. When a less frequent sample schedule is used, the collocated samplers must be operated at least once each week. For each pair of collocated samplers, designate one sampler as the sampler which will be used to report air quality for the site and designate the other as the duplicate sampler. The differences in measured concentration (g/m^3) between the two collocated samplers are used to calculate precision as described in Section 4.1.5.1.

(b) Pb Methods. The operation of collocated samplers at one sampling site must be used to assess the precision of the reference or an equivalent lead method. The procedure to be followed for lead methods is the same as described in 4.1.3.3(a) for the TSP and PM_{10} methods.

4.1.3.4 Accuracy of Manual Methods - (a) TSP and PM_{10} Methods. Each sampling quarter audit the flow rate of each sampler at least once. Audit the flow at the normal flow rate, using a certified flow transfer standard (see reference 39). The flow transfer standard used for the audit must not be the same one used to calibrate the flow of the sampler being audited, although both transfer standards may be referenced to the same primary flow or volume standard. The difference between the audit flow measurement and the flow indicated by the sampler's flow indicator is used to calculate accuracy, as described in Section 4.1.5.2

Great care must be used in auditing high-volume samplers having flow regulators because the introduction of resistance plates in the audit device can cause abnormal flow patterns at the point of flow sensing. For this reason, the orifice of the flow audit device should be used with a normal glass fiber filter in place and without resistance plates in auditing flow regulated high-volume samplers, or other steps should be taken to assure that flow patterns are not perturbed at the point of flow sensing.

(b) Pb Methods. For the reference method (Appendix G of 40 CFR 50) each sampling quarter audit the flow rate of each high-volume lead sampler at least once. Audit the flow rate at one flow rate using a reference flow device described in Section 2.2.8 of reference 39, or a similar flow transfer standard. The device used for auditing must be different from the one used to calibrate the flow of the high-volume sampler being audited. The auditing device and the calibration device may both be referenced to the same primary flow standard. With the audit device in place, operate the high-volume sampler at its normal flow rate. The difference in flow rate (in m^3/min) between the audit flow measurement and the flow indicated by the sampler's normal flow indicator are used to calculate accuracy as described in Section 4.1.5.3.

Great care must be used in auditing high-volume sampler having flow regulators because the introduction of resistance plates in the audit device can cause abnormal flow patterns at the point of flow sensing. For this reason, the orifice of the flow audit device should be used with a normal glass fiber filter in place without resistance plates to audit flow regulated high-volume samplers, or other steps should be taken to assure that flow patterns are not perturbed at the point of flow sensing.

Each sampling quarter, audit the lead analysis using glass fiber filter strips containing a known quantity of lead. Audit samples are prepared by depositing a lead solution on 1.9 cm by 20.3 cm (3/4 inch by 8 inch) unexposed glass fiber filter strips and allowing to dry thoroughly. The audit samples must be prepared using reagents different from those used to calibrate the lead analytical equipment being audited. Prepare audit samples in the following concentration ranges:

Range	Conc. ug Pb/strip	Equivalent Ambient Conc. ug Pb/m^3*
1	100 to 300	0.5 to 1.5
2	600 to 1000	3.0 to 5.0

*Equivalent ambient lead concentration in ug/m^3 is based on sampling at 1.7 m^3/min for 24 hours on 20.3 cm x 25.4 (8 inch x 10 inch) glass fiber filter.

Audit samples must be extracted using the same extraction procedure used for exposed filters.

Analyze at least one audit sample in each of the two ranges each day that samples are analyzed. The difference between the audit concentration (in ug Pb/strip) and the analyst's measured concentration (in ug Pb/strip) are used to calculate analysis accuracy as described in Section 4.1.5.4.

The accuracy of an equivalent method is assessed in the same manner as the reference method. The flow auditing device and lead analysis audit samples must be compatible with the specific requirements of the equivalent method.

4.1.4 Calculations for Automated Methods

4.1.4.1 Single Analyzer Precision - Each organization, at the end of each sampling quarter, shall calculate and report a precision probability interval for each analyzer. Directions for calculations are given below and directions for reporting are given in Section 4.1.6. If monitoring data are invalidated during the period represented by a given precision check, the results of that precision check shall be excluded from the calculations. Calculate the percentage difference (d_i) for each precision check using equation 1.

$$d_i = \frac{Y_i - X_i}{X_i} \times 100 \qquad (1)$$

where: Y_i = analyzer's indicated concentration from the i-th precision check,

X_i = known concentration of the test gas used for the i-th precision check.

For each instrument, calculate the quarterly average (d_j), equation 2, and the standard deviation (S_j), equation 3.

$$\bar{d}_j = \frac{1}{n} \sum_{i=1}^{n} d_i \qquad (2)$$

$$S_j = \sqrt{\frac{1}{n-1} \left[\sum_{i=1}^{n} d_i^2 - \frac{1}{n} \left(\sum_{i=1}^{n} d_i \right)^2 \right]} \qquad (3)$$

Where n is the number of precision checks on the instrument made during the sampling quarter. For example, n should be 6 or 7 if span checks are made bi-weekly during a quarter.

Calculate the 95 percent probability limits for precision using equations 4 and 5.

Upper 95 Percent Probability Limit = $d_j + 1.96\ S_j$ (4)

Lower 95 Percent Probability Limit = $d_j - 1.96\ S_j$ (5)

4.1.4.2 Single Analyzer Accuracy - Each organization, at the end of each sampling quarter, shall calculate and report the percentage difference for each audit concentration for each analyzer audited during the quarter. Directions for calculations are given below (directions for reporting are given in Section 4.1.6).

Calculate and report the percentage difference (d_i) for each audit concentration using equation 1 where Y_i is the analyzer's indicated concentration from the i-th audit check and X_i is the known concentration of the audit gas used for the i-th audit check.

4.1.5 Calculations for Manual Methods

4.1.5.1 Single Instrument Precision for TSP, Pb, and PM_{10}. Estimates of precision for ambient air quality particulate measurements are calculated from results obtained from collocated samplers as described in section 4.1.2.3. At the end of each sampling quarter, calculate and report a precision probability interval, using weekly results from the collocated samplers. Directions for calculations are given below, and directions for reporting are given in Section 4.1.6.

For the paired measurements obtained as described in sections 4.1.2.3(a) and 4.1.2.3(b), calculate the percent difference (d_i) using equation 1a, where Y_i is the concentration of pollutant measured by the duplicate sampler, and X_i is the concentration measured by the sampler reporting air quality for the site. Calculate the quarterly average percent difference (d_j), equation 2, standard deviation (S_j), equation 3, and upper and lower 95 percent probability limts for precision (equations 6 and 7).

$$d_i = \frac{Y_i - Y_i}{(Y_i + X_i)/2} \times 100 \qquad (1a)$$

$$\text{Upper 95 Percent Probability Limit} = d_j + 1.96\ S_j/\sqrt{2} \qquad (6)$$

$$\text{Lower 95 Percent Probability Limit} = d_j - 1.96\ S_j/\sqrt{2} \qquad (7)$$

4.1.5.2 Single Instrument Accuracy for TSP and PM_{10} - Each organization, at the end of each sampling quarter, shall calculate and report the percentage difference for each high-volume or PM_{10} sampler audited during the quarter. Directions for calculation are given below and directions for reporting are given in Section 4.1.6.

For the flow rate audit described in Section 4.1.3.4, let X_i represent the known flow rate and Y_i represent the indicated flow rate. Calculate the percentage difference (d_i) using equation 1.

4.1.5.3 Single Instrument Sampling Accuracy for Pb - Each organization, at the end of each sampling quarter, shall calculate and report the percentage difference for each high-volume lead sampler audited during the quarter. Directions for calculation are given in Section 4.1.5.2 and directions for reporting are given in Section 4.1.6.

4.1.5.4 Single-Analysis-Day Accuracy for Pb - Each organization, at the end of each sampling quarter, shall calculate and report the percentage difference for each Pb analysis audit during the quarter. Directions for calculations are given below and directions for reporting are given in Section 4.1.6.

For each analysis audit for Pb described in Section 4.1.3.4(b), let X_i represent the known value of the audit sample and Y_i the indicated value of Pb. Calculate the percentage difference (d_i) for each audit at each concentration level using equation 1.

4.1.6 Organization Reporting Requirements

At the end of each sampling quarter, the organization must report the following data assessment information: (a) for automated analyzers - precision probability limits from Section 4.1.4.1 and percentage differences from Section 4.1.4.2, and (b) for manual methods - precision probability limits from Section 4.1.5.1 and percentage differences from Sections 4.1.5.2, 4.1.5.3 and 4.1.5.4. The precision and accuracy information for the entire sampling quarter must be submitted with the air monitoring data. All data used to calculate reported estimates of precision and accuracy including span checks, collocated sampler and audit results must be made available to the permit granting authority upon request.

4.2 Quality Assurance for Noncriteria Air Pollutants

At the present time, there are no EPA regulations on quality assurance for PSD monitoring of noncriteria air pollutants. The following are EPA recommendations for a minimum quality assurance program for noncriteria pollutants.

4.2.1 Selection of Method

Selection of the measurement method for noncriteria air pollutants is extremely important. A list of acceptable measurement methods for noncriteria air pollutants is available and may be obtained by writing: U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Quality Assurance Division (MD-77), Research Triangle Park, North Carolina 27711. This list of acceptable methods will be revised at least annually and be available from the above address. Measurement methods considered candidates for the noncriteria pollutant list should be brought to the attention of EPA at the address given above.

4.2.2 Calibration

Calibration procedures described in the acceptable methods should be followed and a schedule for calibrations should be established. In addition, flow measurement devices used to measure sampling rate should be calibrated and a schedule established for recalibration. Calibration procedures for several flow measurement devices (rotameter, critical orifice, mass flow meter, and wet test meter) are described in Section 2.1.2 of reference 39. All calibration procedures should be written and maintained up-to-date by a document control system. A description of one document control system that has been found to be effective is discussed in Section 1.4.1 of reference 38.

4.2.3 Data Validation

Measurement data of poor quality may be worse than no data at all. Therefore, the monitoring organization should establish data validation procedures and implement these procedures to invalidate data of questionable quality. Examples of data validation procedures for criteria pollutants described in Section 2.0.9 of reference 39 may be useful as a guide in establishing data validation procedures for noncriteria pollutants.

4.2.4 Standard and Split Samples

Where possible, standard samples containing the pollutant of interest should be analyzed periodically during the analysis of collected samples. This practice is useful in helping to determine if the analytical system is in control. Splitting samples with another laboratory is quite useful in determining if there are unidentified biases in the analytical system.

5. METEOROLOGICAL MONITORING

5.1 Data Required

The preconstruction review of proposed major emitting facilities will require the use of meteorological data. It is essential that such data be representative of atmospheric dispersion conditions at the source and at locations where the source may have a significant impact on air quality. The representativeness of the data is dependent upon (a) the proximity of the meteorological monitoring site to the area under consideration, (b) the complexity of the topography of the area, (c) the exposure of the meteorological sensors, and (d) the period of time during which the data are collected. More guidance for determining representativeness is presented in reference 42.

A data base representative of the site should consist of at least the following data:

a. hourly average wind speed and direction

b. hourly average atmospheric stability based on Pasquill stability category or wind fluctuations (σ_θ), or vertical temperature gradient combined with wind speed

c. hourly surface temperature at standard height for climatological comparisons and plume rise calculations

d. hourly precipitation amounts for climatological comparisons.

In addition, hourly average mixing heights may be necessary for the air quality impact analysis. In most cases, this may be limited to an extrapolation of twice-daily radiosonde measurements routinely collected by the National Weather Service (NWS). Sections 5.2 and 6.1 contain specific information on instrument exposure and specifications.

Requirements for additional instrumentation and data will depend upon the availability of information needed to assess the effects of pollutant emissions on ambient air quality, soils, vegetation, and visibility in the vicinity of the proposed source. The type, quantity, and format of the required meteorological data will also be influenced by the input requirements of the dispersion modeling techniques used in the air quality analysis. Any application of dispersion modeling must be consistent with the EPA "Guideline on Air Quality Models" [14]. The guideline makes specific recommendations concerning air quality models and data bases. It also specifies those situations for which models, data, and techniques other than those recommended therein, may be applied.

Site-specific data are always preferable to data collected off-site. The availability of site-specific meteorological data permits relatively detailed meteorological analyses and subsequent improvement of dispersion

model estimates. An important source of background information pertaining to on-site meteorological instrumentation is contained in an EPA workshop report [43]. Off-site meteorological data may be used in lieu of site-specific data only if it is agreed by source owner and permit granting authority that the off-site data are reasonably representative of atmospheric conditions in the area under consideration. The off-site meteorological data can sometimes be derived from routine measurements by NWS stations. The data are available as individual observations and in summarized form from the National Climatic Data Center, Federal Building, Asheville, NC 28801. On the other hand, if the nearest source of off-site data is considerably removed from the area under consideration, and especially if there are significant terrain features, urban areas, or large bodies of water nearby, it may be necessary that the required meteorological data be site-specific.

In some cases, it will be necessary that data be collected at more than one site in order to provide a reasonable representation of atmospheric conditions over the entire area of concern. Atmospheric conditions may vary considerably over the area. In some cases, (e.g., complex terrain) it will not be feasible to adequately monitor the entire meteorological field of concern. Then the only recourse is to site the stations in areas where characteristic and significant airflow patterns are likely to be encountered. In any event, one of the meteorological stations should be located so that it represents atmospheric conditions in the immediate vicinity of the source.

Although at least 1 year of meteorological data should be available, a shorter period of record that conforms to the air quality monitoring period of record discussed in Section 2.5 is acceptable when approved by the permit granting authority. If more than 1 year of data is available, it is recommended that such data be included in the analysis. Such a multiyear data base allows for more comprehensive consideration of variations in meteorological conditions that occur from year to year. A 5-year period of record will usually yield an adequate meteorological data base for considering such year-to-year variations.

In all cases, the meteorological data used must be of at least the quality of data collected by the National Weather Service. Desired features of instrumentation for collecting meteorological data are discussed in Section 6.1.

5.2 Exposure of Meteorological Instruments

Measurements of most meteorological parameters are affected by the exposure of the sensor. To obtain comparable observations at different sites, the exposures must be similar. Also, the exposure should be such that the measured parameters provide a good representation of pollutant transport and dispersion within the area that the monitoring site is supposed to represent. For example, if wind flow data over a fairly broad area are desired, the wind sensors should be away from the immediate influence of trees, buildings, steep slopes, ridges, cliffs, or hollows.

The standard exposure of wind instruments over level open terrain is 10 meters above the ground. Open terrain is defined as an area where the distance between the anemometer and any obstruction to the wind flow is at least five times the height of the obstruction. Where a standard exposure is unobtainable at this height, the anemometer should be installed at such a height that its indications are reasonably unaffected by local obstructions and represent as closely as possible what the wind at 10 meters would be in the absence of the obstructions. Detailed guidance on assessing adverse aerodynamic effects due to local obstructions is contained in reference 44. In locating wind sensors in rough terrain or valley situations, it will be necessary to determine if local effects such as channeling, slope and valley winds, etc., are important, or whether the flow outside those zones of influence is to be measured. If the analysis concerns emissions from a tall stack, it may be desirable to avoid the local influences. On the other hand, if pollution from low-level sources is the main concern, the local influences may be important.

If the source emission point is substantially above the standard 10-meter level for wind measurements, additional wind measurements at the height of the emission point and at plume height are desirable. Such measurements are used to determine the wind regime in which the effluent plume is transported away from the source. (The wind speed and direction 50 to 100 meters or more above the surface are often considerably different than at the 10-meter level.) An instrumented tower is the most common means of obtaining meteorological measurements at several elevations in the lower part of the atmospheric boundary layer. For wind instruments mounted on the side of a tower, precautions must be taken to ensure that the wind measurements are not unduly influenced by the tower. Turbulence in the immediate wake of a tower (even a latticetype tower) can be severe. Thus, depending on the supporting structure, wind measuring equipment should be mounted (e.g., on booms) at least two structure widths away from the structure, and two systems mounted on opposite sides of the structure will sometimes be necessary. A wind instrument mounted on top of a tower should be mounted at least one tower width above the top. If there is no alternative to mounting instruments on a stack, the increased turbulence problem [45], must be explicitly resolved to the satisfaction of the permit granting authority.

Atmospheric stability is another key factor in pollutant dispersion downwind of a source. The stability category is a function of static stability (related to temperature change with height), convective turbulence (caused by heating of the air at ground level), and mechanical turbulence (a function of wind speed and surface roughness). A procedure for estimating stability category is given by Turner [46] which requires information on solar elevation angle, cloud cover, ceiling height, and wind speed. The hourly observations at NWS stations include cloud cover, ceiling height, and wind speed. Alternative procedures for estimating stability category may be applied if representative data are available. For example, stability category estimates may be based upon horizontal wind direction fluctuations [47], or vertical gradients of temperature and wind speed [48]. To obtain

a representative reading of the air temperature, the temperature sensor should be protected from thermal radiation from the sun, sky, earth, and any surrounding objects, and must be adequately ventilated. Aspirated radiation shields are designed to provide such protection. (Note that ambient temperature data are also commonly required for plume rise estimates used in dispersion model calculations.)

Mixing height is another parameter that can be important in some cases. Mixing height is the distance above the ground to which relatively free vertical mixing occurs in the atmosphere. For estimating long-term average concentrations, it is adequate to use a representative annual average mixing height [49]. However, in many cases, and especially for estimates of short-term concentrations, twice-daily or hourly mixing height data are necessary. Such data can sometimes be derived [49] from representative surface temperatures and twice-daily upper air soundings collected by selected NWS stations.

Precipitation collectors must be located so that obstructions do not prevent the precipitation from falling into the collector opening or force precipitation into the opening. Several collectors may be required for adequate spatial resolution in complex topographic regimes.

Final rule making entitled "Visibility Protection for Federal Class I Areas," was published in the Federal Register on December 2, 1980. The regulations are applicable to 36 States listed in the action. Although these States are not required to establish visibility monitoring networks, they should consult with the Federal Land Managers to determine monitoring needs. Paragraph 51.305 states that the SIP strategies "must take into account current and anticipated visibility monitoring research, the availability of appropriate monitoring techniques and such guidance as is provided by the Agency." Visibility definitions, monitoring methods, modeling considerations and impact assessment approaches are among the subjects of three EPA reports: (1) "Protecting Visibility: An EPA Report to Congress" [50], (2) "Interim Guidance for Visibility Monitoring" [51], and (3) "Workbook for Estimating Visibility Impairment" [52]. Also, since publication of the final rule, the National Park Service has established a visibility monitoring system. The States or permit granting authority should consider these resources when handling visibility new source review questions.

Additional information and guidance on siting and exposure of meteorological instruments is contained in reference 53.

6. METEOROLOGICAL INSTRUMENTATION

6.1 Specifications

Meteorological instrumentation used for PSD monitoring must yield reasonably accurate and precise data. Accuracies and allowable errors are expressed in this section as absolute values for digital systems; errors in analog systems may be 50 percent greater. For example, an allowable error expressed as 5 percent means the recorded value should be within ±5 percent of the true value for digital systems, and ±7.5 percent for analog systems. Records should be dated, and should be accurate to within 10 minutes. Wind speed and direction (or vector components) should be recorded on a digital data logging system at intervals not to exceed 60 seconds for a given variable; data recorded on continuous strip recorders at intervals not exceeding 60 seconds may be used as backup. These specifications apply to the meteorological instruments used to gather the site specific data that will accompany a PSD permit application. When the use of existing representative meteorological data is approved by the permit granting authority, the instrumentation should meet, as a minimum, NWS standards [54-55].

6.1.1 Wind Systems (horizontal wind)

Wind direction and wind speed systems should exhibit a starting threshold of less than 0.5 meter per second (m/s) wind speed (at 10 degrees deflection for direction vanes). Wind speed systems should be accurate above the starting threshold to within 0.25 m/s at speeds equal to or less than 5 m/s. At higher speeds, the error should not exceed 5 percent of the observed speed (maximum error not to exceed 2.5 m/s). The damping ratio of the wind vane should be between 0.4 and 0.65 and the distance constant should not exceed 5 m. Wind direction system errors should not exceed 5 degrees, including sensor orientation errors. Wind vane orientation procedures should be documented.

6.1.2 Wind Systems (vertical wind)

In complex terrain, downwash of plumes due to significant terrain relief may pose a problem. If such a problem potentially exists, it may be necessary to measure the vertical component of the wind at the proposed site, and as close as possible to stack height. The starting threshold for the vertical wind speed component should be less than 0.25 m/s. Required accuracy for the vertical wind speed component is as specified in Section 6.1.1 for horizontal speeds.

6.1.3 Wind Fluctuations

Determination of the on-site standard deviation of wind fluctuations, or derived standard deviations of cross-plume concentrations may be necessary if dispersion parameters are being developed for use at a specific site. Since the analytical framework within which such wind fluctuations measurements/

statistics are to be incorporated is expected to be unique or applied on a case-by-case basis, approval by the permit granting authority is required and no general requirements regarding specifications are outlined in this guideline. Considerable care is required in the selection of wind instruments and data logging systems, especially in the choice of sampling and averaging times. Thus, response characteristics of wind sensors are especially critical [56,57]. Owners or operators designing programs incorporating these capabilities should submit a statement from a qualified consultant identifying the adequacy of such wind system(s) within the context of the overall PSD ambient monitoring program.

6.1.4 Vertical Temperature Difference

Errors in measured temperature difference should not exceed 0.003 °C/m.

6.1.5 Temperature

Errors in temperatures should not exceed 0.5°C if fog formation, icing, etc., due to water spray or water vapor emitted from the facility may be a problem. Otherwise, errors should not exceed 1.0°C.

6.1.6 Humidity

Atmospheric humidity can be measured and expressed in several ways. If the permit granting authority determines that a significant potential exists for fog formation, icing, etc., due to effluents from the proposed facility, error in the selected measurement technique should not exceed an equivalent dewpoint temperature error of 0.5°C. Otherwise, errors in equivalent dewpoint temperature should not exceed 1.5°C over a dewpoint range of -30°C to +30°C.

6.1.7 Radiation - Solar and Terrestrial

The determination of Pasquill stability class may be based on whether the solar radiation is termed strong, moderate, or slight. Stability class can be determined from sun elevation and the presence, height, and amount of clouds [46], or by using a pyranometer and/or net radiometer during the daytime and a net radiometer at night. Such radiation-to-stability relationships are expected to be site-specific, and the responsibility for demonstrating their accuracy lies with the permit applicant. General accuracy for pyranometers and net radiometers used in a PSD monitoring network is expected to be ± 5 percent.

6.1.8 Mixing Height

Mixing height data may be derived from NWS upper air data. If available data are determined to be inappropriate by the permit granting authority, such data may be obtained on-site by the permit applicant [58]

The instrument system to be used is not specified in this guideline, but its precision and resolution should not exceed the limits associated with NWS radiosonde systems [54,55].

6.1.9 Precipitation

A recording precipitation collector should have a resolution of 0.25 mm (0.01 inches) liquid precipitation per hour at precipitation rates up to 7.6 cm/hour. Accuracy should be within 10 percent of the recorded value. A heated system should be used to assure proper measurement of frozen precipitation. A suitable windscreen should be used.

6.1.10 Visibility

Visibility can be measured within 5 percent of true over visual ranges of about 80 meters to 3 km with available transmissometers. Estimates can be based upon very short path lengths using other types of equipment such as nephelometers [59]. At this time, the combined use of a multi-wavelength telephotometer, integrating nephelometer and particulate monitor, together with color photography, should prove most helpful in documenting baseline visibility related parameters. These as well as other components of a visibility monitoring program, are discussed in reference 51. Reference 50 also contains much background information.

7. QUALITY ASSURANCE FOR METEOROLOGICAL DATA

All equipment should receive an appropriate examination and calibration prior to initial installation to assure the acquisition of the maximum amount of usable data within the error limits specified herein. Inspection, servicing, and calibration of equipment must be scheduled throughout the measurement program at appropriate intervals to assure at least 90 percent data retrieval for each variable measured at sites where continuous air quality monitors are being operated. At remote sites, data retrieval for measured variables should not fall below 80 percent. In addition, the joint frequency for the recovery of wind and stability data should not fall below 90 percent on an annual basis; missing data periods must not show marked correlation with the various meteorological cycles.

Calibration of systems should be accomplished no less frequently than once every 6 months. In corrosive or dusty areas, the interval should be reduced to assure adequate and valid data acquisition.

If satisfactory calibration of a measuring system can be provided only by the manufacturer or in special laboratories, such as wind-tunnel facilities, arrangements should be made for such calibrations prior to acquisition of the equipment. A parts inventory should be maintained at a readily accessible location to minimize delays in restoring operations after system failures.

An independent meteorological audit (by other than one who conducts the routine calibration and operation of the network) should be performed to provide an on-site calibration of instruments as well as an evaluation of (a) the network installation, (b) inspection, maintenance, and calibration procedures, and logging thereof, (c) data reduction procedures, including spot checking of data, and (d) data logging and tabulation procedures. The on-site visit (requiring as little as 1 day in many cases) should be made within 60 days after the network is first in full operation, and a written audit/evaluation should be provided to the owner. This report should be retained by the owner. Any problems should be corrected and duly noted as to action taken in an addendum to the audit report. A reproducible copy of the audit report and the addendum should be furnished with the source construction permit application.

Such independent meteorological audit-evaluations should be performed about each 6 months. The last such inspection should be made no more than 30 days prior to the termination of the measurement program, and while the measurement operation is in progress.

The 1983 publication "Quality Assurance Handbook for Air Pollution Measurement Systems: Volume IV. Meteorological Measurements" [60] should be consulted for more information. Major sections in this volume address (1) quality assurance of the measurement process, (2) methods for judging the suitability of sensor siting, and (3) meteorological data validation.

8. DATA REPORTING

8.1 Air Quality Data Reporting

A summary of the air quality data, the raw air quality data, and the quality assurance data discussed in Section 4.1.6 must be submitted to the permit granting authority at the time of submittal of the PSD application. There should be a prior agreement between the source and the permit granting authority as to whether the raw data should be submitted in addition to a summary of the data. Some sources may also desire to submit data periodically to the permit granting authority for review to identify any problems in the data as they occur. Note that this is not a requirement. The applicant and the permit granting authority should have a prior agreement as to the format and procedure for the data submission. The air quality data should preferably be submitted in SAROAD format and in a machine readable form. A printout of the contents of the tape or cards should also be included. All raw data not previously submitted (i.e., calibration data, flow rates, etc.) should be retained for 3 years and submitted upon request to the permit granting authority.

For continuous analyzers, at least 80 percent of the individual hourly values should be reported by the source in any sampling period. For manual methods (TSP and particulate pollutants), 80 percent of the individual 24-hour values should be reported in any sampling period. This capture rate is important because of the short duration of a PSD monitoring program. In addition, there should not be a correlation between missing data periods and expected highest concentrations.

8.2 Meteorological Data Format and Reporting

Because of the different data requirements for different types of analyses that might be used to evaluate various facilities, there is no fixed format that applies to all data sets. However, a generalization can be made: all meteorological parameters must be collated in chronological order and tabulated according the observation time, and be furnished to the permit granting authority upon request. All meteorological variables that have a SAROAD parameter code should be submitted in SAROAD format. All units should be in the SI system (International System of Units) [61]. All input data (in the format required by the analytical procedures selected) used in, and all results of, the air quality analyses must be furnished to the permit granting authority upon request.

APPENDIX A

PROCEDURES TO DETERMINE IF MONITORING DATA WILL BE REQUIRED FOR A PSD APPLICATION

1. INTRODUCTION

This appendix has been included in this guideline to aid both the reviewing authorities and the source applicants in determining if monitoring data will or will not be required under PSD. The major considerations leading to a monitoring data decision have been simplified for presentation in this appendix. This discussion represents the Federal requirements and the minimum State program requirements. It is important to identify the reviewing authority, whether it be the local or State air pollution control agency, or the Regional Office of EPA for the final requirements. For a complete discussion on the complex PSD issues, the reader is referred to the PSD regulations and the preamble discussion [5,6].

2. PSD PERMIT APPLICATION PROCEDURES

Figure A-1 shows a simplified organizational overview of the procedures to be followed in the preparation of a PSD permit application. Figure A-1 shows that these procedures are divided into seven parts. This division is only for illustrative purposes within this appendix and is intended only to separate the complex procedures into distinct subparts. Within the Part 1-Source Applicability Determination, both candidate new and modified major sources are reviewed to see if PSD review will apply. The Part 2-Pollutant Applicability Determination shows those pollutants emitted from subject sources that may or may not be exempted from further analysis. The Part 3-BACT Analysis is to ensure the application of best available control technology (BACT) on subject pollutants. Air quality analysis covered in Part 4 includes both modeling and monitoring data considerations for certain BACT pollutants. The Part 5-Source Impact Analysis is to demonstrate that the proposed emissions would not cause or contribute to a violation of any NAAQS or PSD increment. The Part 6-Additional Impact Analysis is to ensure that the proposed emissions increases would not impair visibility, or impact on soils and vegetation. Finally, Part 7 represents the complete PSD application which transfers to the permit granting authority the results of all the analysis from the first six parts. Normally, the source applicant will supply all the information including the BACT and air quality analyses to make the necessary determinations. Each of these seven parts is discussed below in Sections 2.1-2.7. Section 3 contains flow diagrams and discussion of the first four parts that pertain to the decision whether monitoring data will or will not be required.

2.1 Part 1 - Source Applicability Determination

The first step in the PSD program is to determine if a proposed new or modified source is subject to the PSD regulations. The first test for PSD applicability is that the proposed construction must involve a major stationary source. Thus, the candidate construction must either be a proposed new major stationary source or involve the modification of an existing major stationary source. The criteria in determining whether

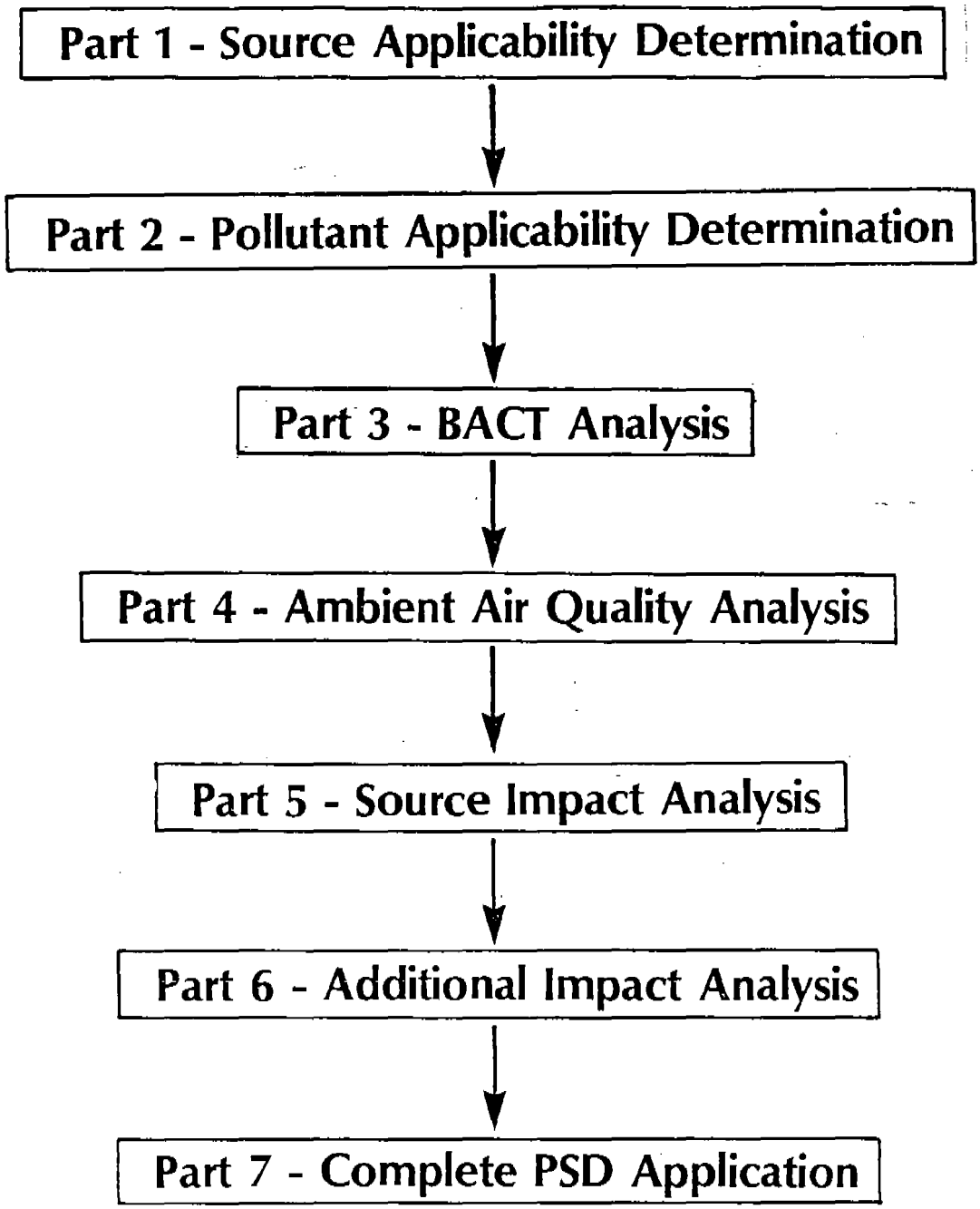


Figure A-1. Simplified procedures for the preparation of a PSD permit application.

the affected source is sufficiently large (in terms of emissions) to be a new major stationary source or major modification is based on consideration of its potential to emit at rates exceeding certain threshold values. Potential to emit is the capability at maximum design capacity to emit a pollutant after the application of all required air pollution control equipment, taking into account all federally enforceable requirements restricting the type or amount of source operation. A major modification is generally a physical change in or a change in the method of operation of a major stationary source which would result in a significant net emissions increase for any regulated pollutant. (There are several changes that are exempted from being considered a major modification.) Also, the proposed source or modification must locate in a PSD area--an area designated as "attainment" or "unclassifiable." If the proposed source or modification would meet certain tests and commence construction in a continuous fashion at the proposed site within a reasonable time, a PSD permit under the August 7, 1980 regulations would not be necessary. Lastly, there are specific new sources and modifications that are exempted from PSD review. All of the above considerations are explained in more detail in Section 3 of this appendix.

If it is determined that a new source or modification is subject to the PSD regulations, then one must proceed to the Part 2-Pollutant Applicability Determination in order to learn how the pollutant-specific requirements of PSD may apply.

2.2 Part 2 - Pollutant Applicability Determination

If a source applicant has determined that a proposed new source or modification would be subject to the PSD requirements, then the applicant must assess whether the pollutants the project would emit are subject to PSD. If a new major stationary source emits pollutants for which the area it locates in is designated nonattainment, then the source is exempt from PSD review for those pollutants. These sources must, however, meet the applicable requirements of new source review (NSR) for each nonattainment pollutant. If a major construction proposed for a PSD area involves only changes for nonattainment pollutants, then the source is not subject to PSD. These sources must meet the appropriate nonattainment NSR under the SIP for the pollutant. Once the question of NSR jurisdiction is resolved, then the PSD review applies to significant emissions increases of regulated air pollutants.

Specific numerical cutoffs which define what emissions increases are "significant" are shown in Table A-1. These emissions rates will be used for pollutants to be emitted from a PSD source unless the new source or modification is to be located within 10 km of a Class I area [1]. For these situations, the proposed source or modification must be prepared to demonstrate that it would not have a significant impact with respect to a Class I area. A Class I significant impact is defined as one microgram per cubic meter (ug/m^3 or more for a 24-hour average. Further details on how the significant emission rates in Table A-1 were derived may be found in the preamble discussion of the PSD regulations [5].

TABLE A-1. SIGNIFICANT EMISSIONS RATES

Pollutant	Emissions Rate (tons/year)
Carbon monoxide	100
Nitrogen oxides	40
Sulfur dioxide	40
Particulate Matter	25 (TSP)
Particulate Matter	15 (PM_{10})
Ozone (volatile organic compounds)	40
Lead	0.6
Asbestos	0.007
Beryllium	0.0004
Mercury	0.1
Vinyl chloride	1.0
Fluorides	3
Sulfuric acid mist	7
Total reduced sulfur (including H_2S)	10
Reduced sulfur (including H_2S)	10
Hydrogen sulfide	10

If the emissions from a new source will be significant, or if the net emissions increase from a proposed modification will be significant, then one must proceed to the Part 3-BACT Analysis for these pollutants.

2.3 Part 3 - BACT Analysis

Any major stationary source or major modification subject to PSD must conduct an analysis to ensure application of best available control technology (BACT) for all applicable pollutants. During each analysis, which will be done on a case-by-case basis, the reviewing authority will evaluate the energy, environmental, economic, and other costs associated with each alternative technology. The reviewing authority will then specify an emissions limitation for the source that reflects the maximum degree of reduction achievable with all these concerns in mind for each pollutant regulated under the Act. In no event can an emission limitation be required which would be less stringent than any applicable standard of performance under 40 CFR Parts 60 and 61.

After the BACT determination, the source must then investigate the need for each pollutant subject to BACT (BACT pollutant) to also undergo the remaining analyses for this pollutant.

2.4 Part 4 - Ambient Air Quality Analysis

Each application by a PSD source or modification must contain an air quality analysis for each BACT pollutant to demonstrate that its new pollutant emissions would not violate either the applicable NAAQS or the applicable PSD increment. This analysis ensures that the existing air quality is better than that required by national standards and that baseline air quality is not degraded beyond the applicable PSD increment. Two narrow exemptions to this requirement are specified in the regulations and involve certain existing sources with low BACT emissions and sources of temporary emissions meeting certain criteria.

In making the above determinations, many PSD sources must first assess the existing air quality for each applicable air pollutant that it emits in the affected area. The requirement to monitor existing air quality may not apply to (a) pollutants for which the new emissions proposed by the applicant would cause impacts less than the significant monitoring concentrations (Table A-2), or (b), situations where the background concentration of the pollutant is below the significant monitoring values. This exemption should not be used when there is an apparent threat to an applicable PSD increment or NAAQS based on modeling alone or when there is a question of adverse impact on a Class I area. When monitoring data are required, the applicant must provide ambient montioring data that represent air quality levels in the year's period preceding the PSD application. Where existing data are not judged representative or adequate, then the applicant must conduct its own monitoring program. Typically, monitoring data are used by applicants to support or extend the assessment made with air quality dispersion modeling.

TABLE A-2. SIGNIFICANT MONITORING CONCENTRATIONS

Pollutant	Air Quality Concentration (ug/m^3) and Averaging Time
Carbon monoxide	575 (8-hour)
Nitrogen dioxide	14 (Annual)
Sulfur dioxide	13 (24-hour)
Particulate Matter	10 (24-hour) for TSP
Particulate Matter	10 (24-hour) for PM_{10}
Ozone	a
Lead	0.1 (3-month)
Asbestos	b
Beryllium	0.001 (24-hour)
Mercury	0.25 (24-hour)
Vinyl chloride	15 (24-hour)
Fluorides	0.25 (24-hour)
Sulfuric acid mist	b
Total reduced sulfur (including H_2S)	c
Reduced sulfur (including H_2S)	c
Hydrogen sulfide	0.2 (1-hour)

[a]No specific air quality concentration for ozone is prescribed. Exemptions are granted when a source's VOC emissions are 100 tons/year.

[b]No acceptable monitoring techniques available at this time. Therefore, monitoring is not required until acceptable techniques are available.

[c]No acceptable monitoring techniques available at this time. However, techniques are expected to be available shortly.

In addition to the above discussion, EPA in general intends to limit the application of air quality models to a downwind distance of 50 kilometers. This is because dispersion parameters commonly in use are based on experiments relatively close to sources, and extending these parameters to long downwind distances results in great uncertainty as to accuracy of the model estimates at such distances. EPA does not intend to analyze the impact of a source beyond the point where the concentrations from the source fall below certain levels (generally based on Class I increments) shown in Table A-3. However, since the 1977 Clean Air Act Amendments provide special concern for Class I areas, any reasonably expected impacts for these areas must be considered irrespective of the 50 km limitation on the above significant values.*

2.5 Part 5 - Source Impact Analysis

The proposed source or modification must demonstrate that significant net emissions increases (including secondary emissions and fugitive emissions), would not cause or contribute to air pollution in the violation of any NAAQS or any applicable maximum allowable increase over the baseline concentration in any area.

2.6 Part 6 - Additional Impact Analysis

An applicant is also required to analyze whether its proposed emissions increases would impair visibility, or impact on soils or vegetation. Not only must the applicant look at the direct effect of source emissions on these resources, but it also must consider the impacts from general commercial, residential, industrial and other growth associated with the proposed source or modification.

2.7 Part 7 - File Complete PSD Application

After completion of the preceeding analyses, the source may submit a PSD application to the permit granting authority. The application, after being judged complete and being reviewed for proper determination of applicability, BACT, and air quality impacts, must undergo adequate

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*It should be noted that there are three separate and distinct sets of values which are considered "significant" within the PSD program:

(a) Significant emissions rates;
(b) Significant monitoring concentrations; and
(c) Significant ambient impacts (including the specific significant Class I area impacts).

As pointed out, each set of values has a different application, and therefore, this guideline has been worded to clarify the appropriate values to be used while assessing the need to collect monitoring data.

TABLE A-3. SIGNIFICANT AMBIENT AIR QUALITY IMPACTS

	Averaging Time				
Pollutant	Annual	24-Hour	8-Hour	3-Hour	1 Hour
SO_2	1 ug/m^3	5 ug/m^3	--	25 ug/m^3	--
PM_{10}	1 ug/m^3	5 ug/m^3	--	--	--
NO_2	1 ug/m^3	--	--	--	--
CO	--	--	0.5 mg/m^3	--	2 mg/m^3

NOTE: This table does not apply to Class I areas. A significant impact for Class I areas is 1 ug/m^3 on a 24-hour basis for PM_{10} and SO_2.

public participation. The regulations solicit and encourage participation by the general public, industry, and other affected persons impacted by the proposed major stationary source or major modification. Specific public notice requirements, including a public comment period and the opportunity for a public hearing must be met before the PSD review agency takes final action on a PSD application. The public notice must indicate whether the reviewing authority has proposed approval, denial, or conditional approval of the proposed major source or major modification. Consideration is given to all comments received provided they are relevant to the scope of the review.

The source shall also submit all information necessary to perform any analysis in Parts 1-6 above or make any determinations required in Parts 1-6. Such information shall include (a) a description of the nature, location, design capacity, and typical operating schedule of the proposed source or modification, including specifications and drawings showing its design and plant layout, (b) a detailed schedule for construction of the proposed source or modification, and (c) a detailed description as to what system of continuous emission reduction is planned for the proposed source or modification, emission estimates, and any other information necessary to determine that best available control technology would be applied. The proposed source or modification shall also provide information on (a) the air quality impact of the proposed source or modification, including meteorological and topographical data necessary to estimate such impact, and (b) the air quality impacts, and the nature and extent of any or all general commercial, residential, industrial, and other growth which has occurred since August 7, 1977 in any area the proposed source or modification would affect.

3. DECISIONS FOR MONITORING DATA REQUIREMENTS

Figure A-1 and the discussion that followed in Section 2 provided an overview of the various activities relating to a PSD permit application. This section will go into more detail on those activities that need to be considered in deciding if air quality monitoring data will be required.

It should be noted that the procedures described in this appendix do not include any details on how the modeling analyses are to be conducted but only indicate at what points (boxes) the results of such analyses are necessary. Also, while these procedures lead to a determination of when air quality monitoring is likely to be required, they do not lead to a decision as to when meteorological monitoring is necessary (for model input). Guidance on the requirements and procedures for conducting modeling analyses is contained in reference 14. Section 5 of this guideline describes general meteorological monitoring requirements, and reference 62 also provides further guidance on this subject.

Figures A-2 and A-3 show various steps that must be made for a proposed PSD source or modification in order to assess how the monitoring data requirement might apply. The decisions in these flow diagrams must be applied separately for each regulated pollutant that would be emitted from a proposed source or modification. Boxes 1-14 apply to Figure A-2 and boxes 15-29 apply to Figure A-3

Box 1. Is proposed source a major stationary source or major modification locating in a PSD area?

A major stationary source is defined as any one of 28 source categories (Table A-4) which emits, or has the potential to emit, 100 tons per year or more of any pollutant regulated under the Act. In addition, the definition includes any other stationary source which emits, or has the potential to emit, 250 tons per year or more of any regulated pollutant. Finally, major stationary source also means any physical change occurring at a stationary source (which prior to the change is not major) if the change by itself would be major. That is, the change itself would result in an equivalent stationary source which would emit 100 tons per year or more for any pollutant regulated under the Act for any one of the 28 source categories (Table A-4), or 250 tons per year for any other stationary source. The pollutants regulated under the Act were shown in Part 2-Pollutant Applicability Determination.

A stationary source generally includes all pollutant-emitting activities which belong to the same industrial grouping, are located on contiguous or adjacent properties, and are under common control. Pollutant activities which belong to the same major group as defined in a standard industrial classification scheme developed by the Office of Management and Budget are considered part of the same industrial grouping.

The rest of the PSD size applicability for proposed new stationary sources is simply that the candidate source would be a major stationary

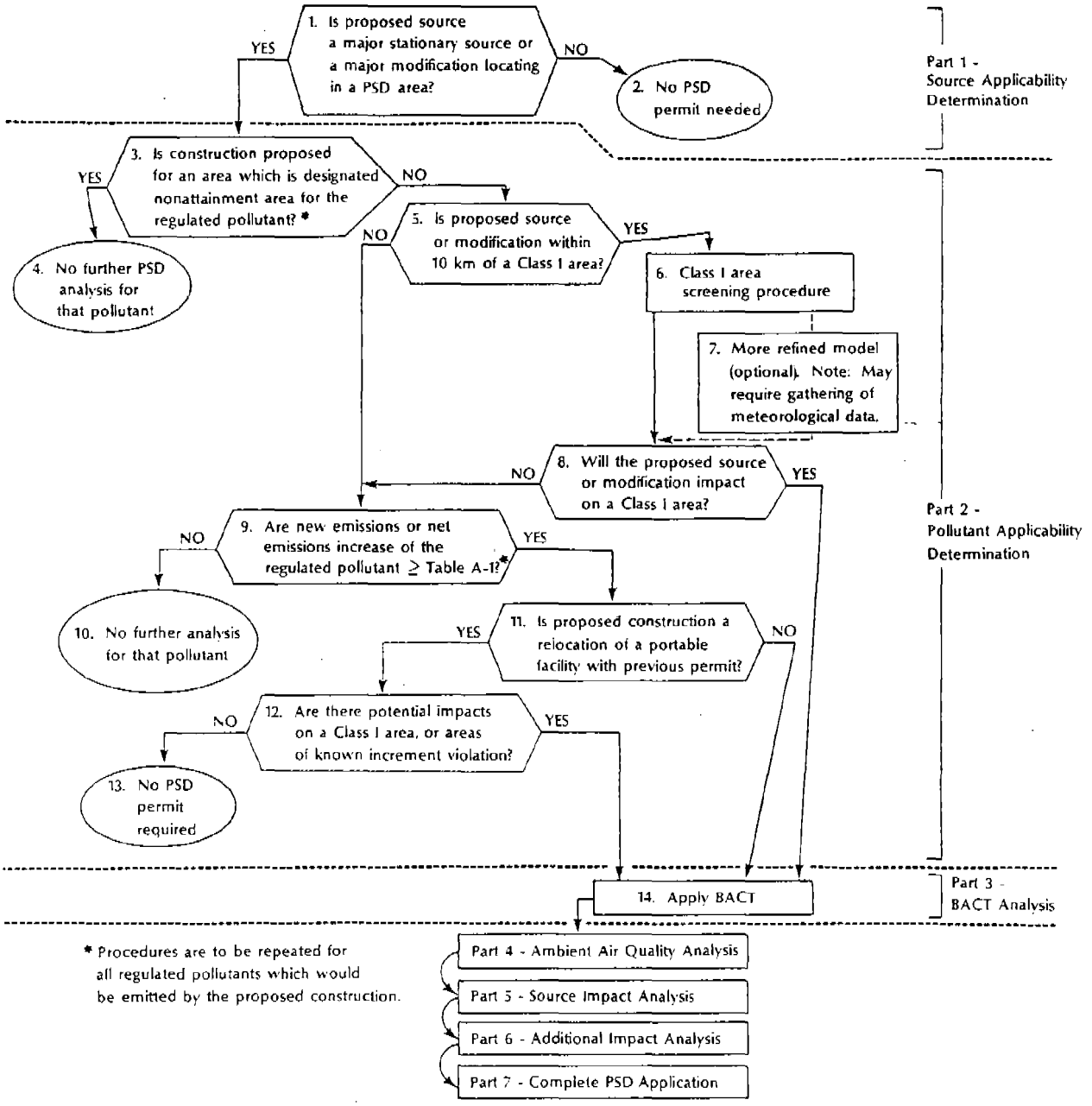

Figure A-2. Procedures used to determine the monitoring data requirement.

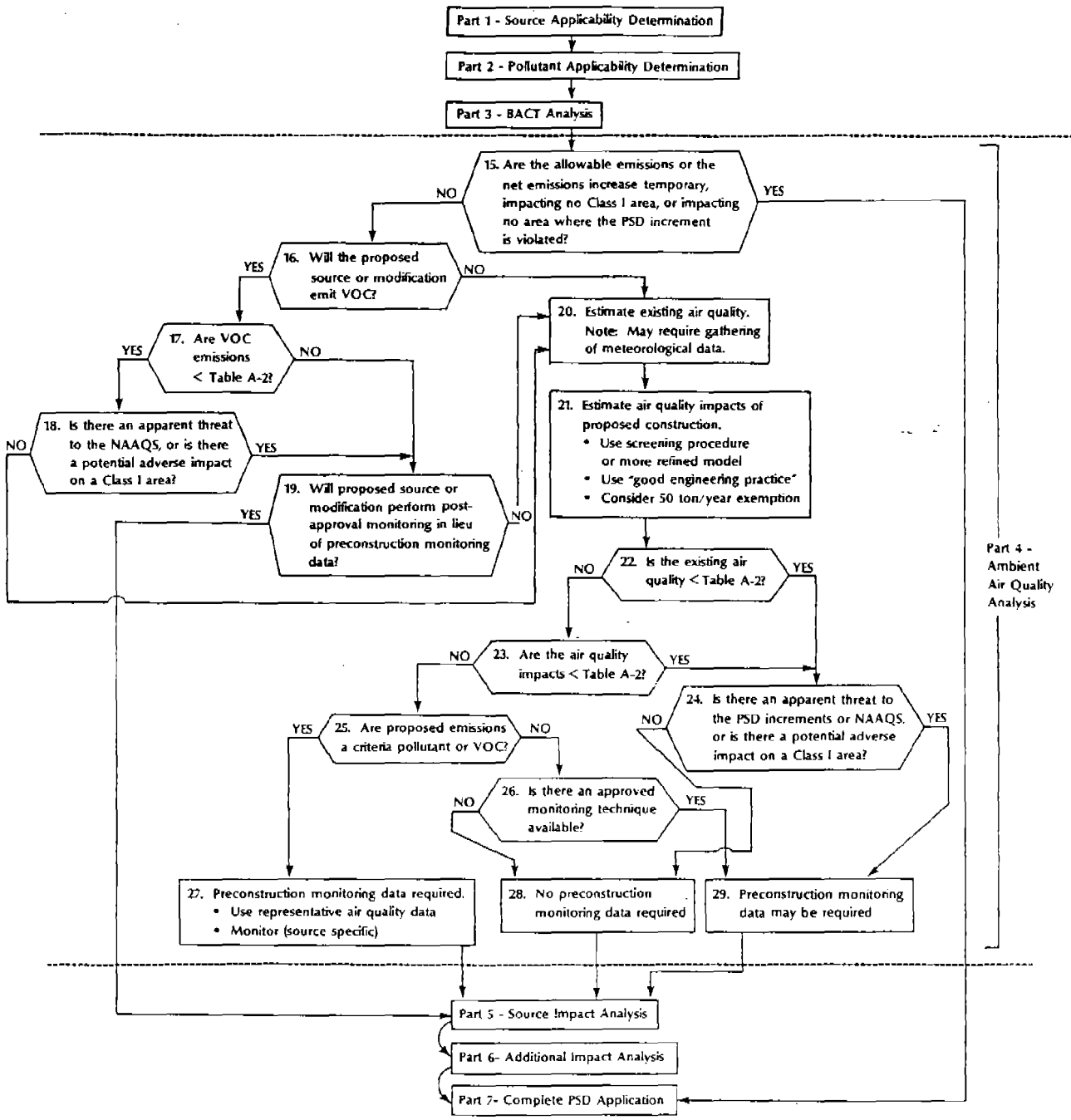

FIGURE A-3. PROCEDURES USED TO DETERMINE THE MONITORING DATA REQUIREMENT.

TABLE A-4. MAJOR STATIONARY SOURCES

1. Fossil-fuel fired steam electric plants of more than 250,000,000 British thermal units per hour heat input
2. Coal cleaning plants (with thermal dryers)
3. Kraft pulp mills
4. Portland cement plants
5. Primary zinc smelters
6. Iron and steel mill plants
7. Primary aluminum ore reduction plants
8. Primary copper smelters
9. Municipal incinerators capable of charging more than 250 tons of refuse per day
10. Hydrofluoric acid plants
11. Sulfuric acid plants
12. Nitric acid plants
13. Petroleum refineries
14. Lime plants
15. Phosphate rock processing plants
16. Coke oven batteries
17. Sulfur recovery plants
18. Carbon black plants (furnace process)
19. Primary lead smelters
20. Fuel conversion plants
21. Sintering plants
22. Secondary metal production plants
23. Chemical process plants
24. Fossil-fuel boilers (or combinations thereof) totaling of more than 250,000,000 British thermal units per hour heat imput
25. Petroleum storage and transfer units with a total storage capacity exceeding 300,000 barrels
26. Taconite ore processing plants
27. Glass fiber processing plants
28. Charcoal production plants

source in terms of its potential to emit. The applicability rules for determining whether a major modification would occur are more complex.

A "major modification" is generally a physical change in or a change in the method of operation of a major stationary source which would result in a significant net emissions increase in the emissions of any regulated pollutant. In determining if a proposed increase would cause a significant net increase to occur, several detailed calculations must be performed. First, the source owner must quantify the amount of the proposed emissions increase. This amount will generally be the potential to emit of the new or modified unit. Second, the owner must document and quantify all emissions increases and decreases that have occurred or will occur contemporaneously (generally within the past five years) and have not been evaluated as part of a PSD review. The value of each contemporaneous decrease and increase is generally determined by subtracting the old level of actual emissions from the new or revised one. Third, the proposed emissions increase and the unreviewed contemporaneous changes must then be totalled. Finally, if there is a resultant net emissions increase that is larger than values specified in Table A-1, the modification is major and subject to PSD review.

Certain changes are exempted from the definition of major modification. These include: (a) routine maintenance, repair and replacement; (b) use of an alternative fuel or raw material by revision of an order under sections 2(a) and (b) of the Energy Supply and Environmental Coordination Action of 1974 (or any superseding legislation); (c) use of an alternative fuel by reason of an order or rule under section 125 of the Clean Air Act; (d) use of an alternative fuel at a steam generating unit to the extent it is generated from municipal solid waste; (e) use of an alternative fuel or raw material which the source was capable of accommodating; before January 6, 1975 or which the source is approved to use under any permit issued under 40 CFR 52.21, or under regulations approved pursuant to 40 CFR 51.24; and (f) an increase in the hours of operation, or the production rate. The last two exemptions, (e) and (f), can be used only if the corresponding change is not prohibited by certain permit conditions established after January 6, 1975.

If the size of a proposed source or modification thus qualifies as major, its prospective location or existing location must also qualify as a PSD area, in order for PSD review to apply. A PSD area is one formally designated by the state as "attainment" or "unclassifiable" for any pollutant for which a national ambient air quality standard exists. This geographic applicability test generally does not take into account what new pollutant emissions caused the construction to be major. It looks simply at whether the source is major for any pollutant and will be located in a PSD area. The one exception is that if a major stationary source emits only non-attainment pollutants, then no PSD review would apply.

If a proposed source or modification would be subject to PSD review based on size, location, and pollutants emitted, it still may escape the PSD review requirements under certain grandfather provisions under 40 CFR

52.21(i). For example, a proposed source or modification that was not subject to the 1978 PSD rules and had received all necessary Federal, State and local air permits before August 7, 1980, would not be subject to the 1980 regulations. (See the PSD regulations for other exemptions.)

Finally, the PSD regulations contain some specific exemptions for some forms of source construction. The requirements of the PSD regulations do not apply to any major stationary source or major modification that is (a) a nonprofit health or educational institution (only if such exemption is requested by the governor), or (b) a portable source which has already received a PSD permit and proposes relocation, or the source or modification would be a major stationary source or major modification only if fugutive emissions, to the extent quantifiable, are considered in calculating the potential to emit of the stationary source or modification and the source does not belong to any of the categories listed in Table A-4.

Box 2. No PSD permit needed.

If the source has met the appropriate deadlines for construction; and is not a major stationary source, a major modification, is not located in a PSD area, or is not subject to the specific exemptions mentioned above, the PSD program is not applicable, and therefore, no PSD permit is needed.

Box 3. Is construction proposed for an area which is designated nonattainment area for the regulated pollutant?

If the project is a major stationary source or a major modification, the prospective location must also qualify as a PSD area in order for the PSD review to apply. A PSD area is defined as an area formally designated by the State as "attainment" or "unclassifiable" for any pollutant for which a NAAQS exists. An area not classified as either "attainment" or "unclassifiable" would be classified as "nonattainment". If the proposed construction is in a nonattainment area for any pollutant, proceed to box 4 for that pollutant; for all other regulated pollutants, proceed to box 5.

Box 4. No further PSD analysis for that pollutant.

If the proposed major stationary source or major modification will emit pollutants from an area that has been designated as "nonattainment", then the proposed source or modification is exempt from further PSD review for only those pollutants. However, the proposed source or modification must meet the applicable preconstruction requirements for each nonattainment pollutant. (See 40 CFR 51.18 and 40 CFR 52.24.)

The pollutant applicability determination would be continued for all other regulated pollutants (except nonattainment pollutants) emitted by a proposed major stationary source or major modification by proceeding to box 5.

Box 5. Is proposed source or modification within 10 km of a Class I area?

The PSD regulations [40 CFR 51.24(b)(23)(iii) and 40 CFR 52.21(b)(23)(iii)] require that a proposed source or modification, which plans to construct within 10 km of a Class I area must demonstrate that if it would not impact the area, (less than 1 ug/m^3) even if the proposed emissions are below the applicable significant emissions rates listed in Table A-1. If the proposed source or modification is within 10 km of a Class I area, proceed to box 6; if not, proceed to box 9.

Box 6. Class I area screening procedure.

If the proposed source or modification is within 10 km of a Class I area, then the screening procedures described in reference 62 may be used to estimate the impact on the Class I area. This screening procedure is based on a simple but conservative model for estimating each concentration due to the emissions from the proposed source or modification.

Box 7. More refined model (optional).

A proposed source or modification may choose not to accept or use the concentration estimates derived from the screening procedures in box 6, and may elect to use a more refined model which would more adequately reflect the impact on the Class I area from the proposed source or modification. It should be emphasized that in order to perform a refined modeling analysis, it may be necessary to collect 1 year of on-site meteorological data for the model input if an adequate amount of representative data are not already available. The application of any model used in this analysis must be consistent with reference 14 as discussed in section 5.1. The application of any different model must be approved by EPA in order to avoid any delays in the processing of the permit application. Applicants should consult with the reviewing authority before investing considerable resources in the use of the different models. Therefore, the documentation and specific description of the model should be provided to the reviewing authority before the results are submitted.

The concentration estimates from the screening procedure or the refined model, are subsequently used in the Part 4-Ambient Air Quality Analysis and Part 5-Source Impact Analysis.

Box 8. Will the proposed source or modification impact on a Class I area?

If a proposed source or modification is within 10 km of a Class I area, the proposed source or modification must be prepared to demonstrate for each regulated pollutant it would emit that there would be no significant impact on the Class I area. Significant impact is defined in the PSD regulations [40 CFR 51.24(b)(23)(iii) and 40 CFR 52.21(b)(23)(iii)] as 1 microgram per cubic meter (ug/m^3) or more, 24-hour average.

Box 9. Are new emissions or net emissions increase of the regulated pollutant $\geq$Table A-1?

If the proposed source or modification is not within 10 km of a Class I area, or if the proposed source is within 10 km of a Class I area and has no significant impact on the Class I area, then the emissions for each pollutant from the proposed source of modification are compared to the significant emissions rates in Table A-1.

Box 10. No further analysis for that pollutant.

If the emissions from the proposed source or modification are not significant as defined in Table A-1, no further analysis is required for that pollutant. However, a similar review must be performed for all other regulated pollutants by proceeding to box 5 for the next pollutant.

Box 11. Is proposed construction a relocation of a portable facility with previous permit?

This question is actually an applicability question that is normally considered under the Part 1-Source Applicability Determination. However, there are certain other questions (see boxes 3, 5 and 8 of Figure A-2) which are normally asked under pollutant applicability that are also germane to permitting a portable facility relocation. Thus, the reason for including box 11 in Part 2.

The source must be a portable facility which has previously received a permit under the PSD regulations, the owner proposes to relocate the facility, and emissions at the new location would be temporary (not exceeding its allowable emissions). If the facility meets these requirements, then proceed to box 12; if not, proceed to box 14.

Box 12. Are there potential impacts on a Class I area, or areas of known increment violation?

The emissions from the portable source should not exceed its allowable emissions, and the emissions from the temporary source should impact no Class I area and no area where an applicable increment is known to be violated. If there are potentially adverse impacts on a Class I area, or significant impacts on areas of known increment violation, proceed to box 14; if not, proceed to box 13.

Box 13. No PSD permit required.

If there are no potential impacts on a Class I area, or areas of known increment violation, no PSD permit is required.

Box 14. Apply BACT.

"Best available control technology" means an emissions limitation (including a visible emission standard) based on the maximum degree of

reduction for each pollutant subject to regulation under the Act which would be emitted from any proposed major stationary source or major modification which the Administrator, on a case-by-case basis, taking into account energy, environmental, and economic impacts and other costs, determines 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 of any pollutant which would exceed the emissions allowed by any applicable standard under 40 CFR Parts 60 and 61. If the Administrator determines that technological or economic limitations on the application of measurement methodology to a particular emissions unit would make the imposition of an emissions standard infeasible, a design, equipment, work practice, operational standard, or combination thereof, may be prescribed instead to satisfy the requirement for the application of best available control technology. Such standard shall, to the degree possible, set forth the emissions reduction achievable by implementation of such design, equipment, work practice or operation, and shall provide for compliance by means which achieve equivalent results.

Box 15. Are the allowable emissions or the net emissions increase temporary, impacting no Class I area, or impacting no area where the PSD increment is violated?

Temporary emissions are defined as emissions from a temporary source that would be less than 2 years in duration, unless the Administrator determines that a longer time period would be appropriate. If all of the conditions above are not met, proceed to box 16; if they are met, proceed to Part 7-Complete PSD Application.

Box 16. Will the proposed source or modification emit VOC?

If the proposed source or modification will emit VOC, proceed to box 17; if not, proceed to box 20. Also proceed to box 20 if the pollutants are TSP, PM_{10}, SO_2, CO, NO_2, or Pb.

Box 17. Are VOC emissions < Table A-2?

If the VOC emissions rates from the proposed source or modification are less than the value in Table A-2 (100 tons/year), proceed to box 18; if not, proceed to box 19.

Box 18. Is there an apparent threat to the NAAQS, or is there a potential adverse impact on a Class I area?

If the projected air quality after construction is equal to or greater than 90 percent of the NAAQS, a threat to the NAAQS would generally exist. Potential adverse impacts on a Class I area must be determined on a case-by-case basis by the permit granting authority. Therefore, if there is an apparent threat to the NAAQS, or if there are potential adverse impacts on a Class I area, then proceed to box 19; if not, proceed to box 20.

Box 19. Will proposed source modification perform postapproval monitoring in lieu of preconstruction monitoring data?

The PSD regulations [40 CFR 51.24(m)(1)(v) and 40 CFR 52.21(m)(1)(vi)] give special considerations regarding ozone monitoring data to new or modified sources of volatile organic compounds which have satisfied all conditions of 40 CFR 51, Appendix S, section IV. This section generally requires affected sources to meet lowest achievable emission rate limitations, secure emissions offsets which provide an overall net air quality improvement, and ensure all other major sources in the same State are in compliance with the applicable SIP. If a proposed source or modification has met all of the above conditions for VOC, then the proposed source or modification may provide postapproval monitoring data for ozone in lieu of providing preconstruction data. Postapproval monitoring data are data collected after the date of approval of the PSD application. However, in no case should the postapproval monitoring be started later than 2 years after the start-up of the new source or modification.

If the proposed source or modification will provide postapproval monitoring, proceed to the Part 5-Source Impact Analysis; if not, proceed to box 20 for the remainder of the ambient air quality analysis.

Box 20. Estimate existing air quality.

The proposed source or modification must perform an initial analysis to estimate the existing air quality concentrations. The screening procedures described in reference 62 may be used. The screening procedures are based on simple models for estimating air quality due to the emissions from existing and approved but not yet built sources. A proposed source or modification may choose not to accept or use the concentration estimates derived from the screening procedure above, and may elect to use a more refined model which would more adequately reflect the impact from existing sources. It should be emphasized that in order to perform a refined modeling analysis, it is generally necessary to collect 1 year of on-site meteorological data for the model input. The application of any model used in this analysis must be consistent with reference 14 as discussed in section 5.1. The application of any model should be approved by the permit granting authority to avoid any future delays in the processing of the permit application. Therefore, the documentation of the specific description of the model should be provided to the permit granting authority before the results are submitted.

The concentration estimates from the screening procedure or the optional refined model will be used in the remaining portions of the ambient air quality analysis.

Box 21. Estimate air quality impacts of proposed construction.

The proposed source or modification must estimate its air quality impacts to demonstrate that its new pollutant emissions would not violate either the applicable NAAQS or the applicable PSD increment. The proposed source or modification must use the screening procedures or more refined model, consider "good engineering practice" for stack height, and consider the TSP and SO_2 increment exclusion for Class II areas under 50 tons per year exemption. These factors are discussed in more detail below.

(a) Screening procedure or more refined model.

If the proposed source or modification used the screening procedure or more refined model in box 6 or 7 previously to estimate the impact, then those results may be used in this impact analysis. If the screening procedure or more refined model was not previously determined, then the screening procedures described in reference 62 may be used. This screening procedure is based on a simple model for estimating each concentration due to the emissions from the proposed source or modification. A proposed source or modification may choose not to accept or use the concentration estimates derived from the screening procedure above, and may elect to use a more refined model which would more adequately reflect the impact from the proposed source or modification. It should be emphasized that in order to perform a refined modeling analysis, it is generally necessary to collect 1 year of on-site meteorological data for the model input. The application of any model used in this analysis must be consistent with reference 14 as discussed in Section 5.1. The application of any model should be approved by the permit granting authority to avoid any future delays in the processing of the permit application. Therefore, the documentation and specific description of the model should be provided to the permit granting authority before the results are submitted.

The concentration estimates from the screening procedure or the optional refined model will be used in the remaining portions of the ambient air quality analysis.

(b) "Good engineering practice" (GEP) for stack height.

The 1978 PSD regulations [1] provide for requiring GEP in the impact analysis for stack heights. The degree of emission limitations required for the control of any air pollutant would not be affected by stack heights (in existence after December 31, 1970) as exceeds good engineering practice, or any other dispersion techniques implemented after then.

(c) Consider 50 tons per year exemption.

The PSD regulations [40 CFR 51.24(i)(7) and 40 CFR 52.21(i)(7)] as they apply to a major modification exempt PM_{10} and SO_2 from the Class II increment consumption review if all of the following conditions are met:

(1) the net increase of all pollutants regulated under the Act after application of BACT would be less than 50 tons/year, (2) no pollutant would be causing or contributing to a violation of the standards (NAAQS), and (3) source must have been in existence on March 1, 1978. The results of the impact analysis as described in this box will be used for subsequent portions of the ambient air quality analysis.

Box 22. Is the existing air quality < Table A-2?

The proposed source or modification must determine the existing air quality concentration in the area of impact of the proposed source or modification before construction for each applicable pollutant. Modeling by itself or in conjunction with monitoring data would be used for this determination. Application of these models must be consistent with reference 14.

If the proposed source or modification is remote and not affected by other readily identified man-made sources, two options for determining existing air quality concentrations from existing data are available. The first option is to use air quality data collected in the vicinity of the proposed source or modification, the second option is to use average measured concentrations from a "regional" site to establish a background concentration. Additional guidance on determining the background air quality concentrations may be found in reference 14. See also the discussion or use of representative air quality data in Section 2.4 of this guideline.

If the existing air quality is less than the values in Table A-2, proceed to box 24; if not, proceed to box 23.

Box 23. Are the air quality impacts < Table A-2?

The projected impact of the proposed source or modification was previously determined by the screening procedure or refined model estimates. These modeled concentrations are compared to the significant monitoring concentrations shown in Table A-2. If these modeled concentrations are less than the values in Table A-2, proceed to box 24; if not, proceed to box 25.

Box 24. Is there an apparent threat to PSD increments or NAAQS, or is there a potential adverse impact on a Class I area?

An apparent threat to a PSD increment is consumption by the proposed source or modification of 90 percent or more of the remaining allowable increment. An apparent threat to the NAAQS is when the projected air quality after construction is equal to or greater than 90 percent of the NAAQS. Potential adverse impacts on a Class I area must be determined on a case-by-case basis by the permit granting authority.

Therefore, if there is an apparent threat to PSD increments or NAAQS, or if there is a potential adverse impact on a Class I area, proceed to box 29; if not, proceed to box 28.

Box 25. Are proposed emissions a criteria pollutant or VOC?

Determine if the pollutant is a criteria pollutant (TSP, PM_{10}, SO_2, CO, NO_2 or Pb) or VOC. If the pollutant is a criteria pollutant or VOC, proceed to box 27; if not, proceed to box 26.

Box 26. Is there an approved monitoring technique available?

Acceptable measurement methods currently exist for some noncriteria pollutants, while other methods are currently under review and have not been designated as an acceptable measurement method. Section 2.6 of this guideline discussed the designation of acceptable measurement methods for noncriteria pollutants. If an acceptable measurement method does exist, proceed to box 29; if not, proceed to box 28.

Box 27. Preconstruction monitoring data required.

Preconstruction air quality monitoring data are required for this part of the ambient air quality analysis. The proposed source or modification has the option of using representative air quality data or monitoring. Considerations and constraints on the use of existing data were discussed in Section 2.4 of this guideline. It should be noted that a dispersion model may be used in verifying the representativeness of the data. If a proposed source or modification chooses to monitor instead of using representative air quality data, then the specifics to be followed on network design, probe siting, quality assurance, number of monitors, etc., were previously discussed in this guideline.

The monitoring data required in this box will be used in Parts 5, 6 and 7 of the PSD permit application.

Box 28. No preconstruction monitoring data required.

If there is no approved monitoring technique for the noncriteria pollutants, or if there is no apparent threat to PSD increments or NAAQS, or if there is no potentially adverse impact on a Class I area, then generally no preconstruction monitoring data will be required. However, proceed to the Part 5-Source Impact Analysis for remaining analyses.

Box 29. Preconstruction monitoring data may be required.

The permit granting authority must determine on a case-by-case basis if monitoring data will be required when there is an apparent threat to PSD increments or NAAQS, or when there is a potential adverse impact on a Class I area. Special attention must be given to Class I areas where the proposed source or modification would pose a threat to the remaining allowable increment. For those situations where the air quality concentration before construction is near the concentrations shown in Table A-2 and there are uncertainties associated with this air quality determination then precon-

struction air quality monitoring data may be required. Some situations where noncriteria monitoring may be required were discussed in Section 2.1.3 of this guideline.

Regardless of the monitoring data decision, proceed on to the Part 5-Source Impact Analysis for remaining analyses.

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16. ABSTRACT

Ambient air monitoring guidelines are described for sources that may be required to monitor the air quality under the Prevention of Significant Deterioration (PSD) regulations. Some step-by-step discussion is presented for a source to determine if monitoring will be necessary. Situations where existing air quality and meteorological data, modeling, and use of assumed background concentrations for certain areas may be used in lieu of monitoring, are shown.

If a source must undertake a monitoring program, general guidance is given for pollutants to be monitored, number and location of monitoring sites, equipment, frequency and duration of sampling, and data reporting. More detailed guidance is discussed for air quality monitoring probe siting criteria for various pollutants, meteorological monitoring, and quality assurance procedures.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Draft

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August 6, 2007

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Human and Ecological Risk Assessment of Coal Combustion Wastes – Executive Summary

The U.S. Environmental Protection Agency (EPA) is evaluating management options for solid wastes from coal combustion (e.g., fly ash, bottom ash, slag). As part of this effort, EPA is evaluating whether current management practices for coal combustion waste (CCW) pose risks to human health or ecological receptors. To inform this objective, EPA has conducted a nationwide assessment of the risks posed by CCW disposal practices across the country.

This report describes the results of the tiered, site-based, probabilistic (Monte Carlo) risk assessment of onsite CCW disposal practices at coal-fired power plants across the United States. These landfills and surface impoundments represent disposal practices for CCW reported in 1995. Although EPA acknowledges that management practices for CCW have improved since 1995, as documented in U.S. Department of Energy (DOE) (2006), EPA believes that characterizing risks from facilities observed in 1995 provides a snapshot of the potential risks from CCW disposal and can provide useful information as EPA evaluates CCW management options. In addition, the data available on these facilities' locations, environmental characteristics, and waste management units (WMUs) allow EPA to apply a site-based risk assessment approach that the agency believes characterizes the risks to human health and the environment from disposing CCW in landfills and surface impoundments.

In summary, this CCW risk assessment evaluates potential risk results at the 50th and 90th percentile exposure level, adopting a risk criteria of 10^{-5} for excess cancer risks. Potential noncancer and ecological risks are also evaluated at the 50th and 90th percentile levels, adopting a hazard quotient (HQ) risk criteria greater than 1 for noncancer effects to both human and ecological receptors. Overall, when all types of landfills and surface impoundments (as observed in 1995) are evaluated in aggregate, the risk at the 90th percentile exceeds the risk criteria for cancer and noncancer risks for certain constituents. There is no potential risk above the risk criteria (cancer and noncancer) found at the 50th percentile. The risk assessment also suggests that 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.

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 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.

Composite liners, which are used in the majority of new facilities constructed after 1995, effectively reduce risks from all pathways and constituents below the risk criteria (cancer and noncancer) for both landfills and surface impoundments[1].

Risks from clay-lined units, as modeled, are about one-third to one-half the risks of unlined

[1] 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, but are still above the risk criteria used for this analysis.

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.

Background

EPA has conducted risk assessments to evaluate the environmental risks from CCW management practices,[2] including CCW disposal in landfills and surface impoundments. Although EPA determined (in April 2000) that certain CCWs were not subject to hazardous waste regulations and therefore would be subject to regulation as nonhazardous wastes, EPA did not specify regulatory options at that time. This risk assessment was conducted to identify and quantify human health and ecological risks that may be associated with current disposal practices for high-volume CCW, including fly ash, bottom ash, boiler slag, flue gas desulfurization (FGD) sludge, coal refuse waste, and wastes from fluidized-bed combustion (FBC) units. These risk estimates will help inform EPA's decisions about how to treat CCWs under Subtitle D of the Resource Conservation and Recovery Act.

Purpose and Scope of the Risk Assessment

The purpose of this risk assessment is to identify potential risks associated with CCW constituents, waste types, receptors, and exposure pathways, and to provide information about those scenarios that EPA can use to develop CCW management options.

The scope of this risk assessment is CCWs managed onsite at utility power plants. EPA's *Report to Congress: Wastes from the Combustion of Fossil Fuels* (U.S. EPA, 1999a) reports that there are 440 coal-fired utility power plants in the United States. Although these plants are concentrated in the East, they are found in nearly every state, with a broad variety of climate, geologic, and land use settings. The large volumes of waste generated by these plants

[2] Details on EPA's previous CCW work can be found at http://www.epa.gov/epaoswer/other/fossil/ index.htm.

are typically managed onsite in landfills and surface impoundments. This risk assessment was designed to develop national human and ecological risk estimates that are representative of onsite CCW management settings throughout the United States.

Risk Assessment Methodology

To estimate the risks posed by the onsite management of CCW, this risk assessment determined the release of CCW constituents from landfills and surface impoundments, estimated the concentrations of these constituents in environmental media surrounding coal-fired utility power plants, and estimated the risks that these concentrations pose to human and ecological receptors. To evaluate the significance of these risks, the risk criteria adopted for this assessment are:

- An estimate of the excess lifetime cancer risk for individuals exposed to carcinogenic (cancer-causing) contaminants of 1 chance in 100,000 (10^{-5} excess cancer risk)
- An HQ (the ratio of predicted intake levels to safe intake levels) greater than 1 for constituents that can produce noncancer human health effects
- An HQ greater than 1 for constituents with adverse effects to ecological receptors.

In support of this risk assessment, EPA assembled a constituent database that includes leachate and total waste analyses for 41 CCW constituents taken from more than 140 CCW disposal sites around the country. The CCW risk assessment subjected these waste and leachate constituent concentrations to a tiered risk assessment methodology (Figure ES-1) that implemented the following steps to assess the human and ecological risk of CCWs:

- **Hazard Identification**, which collected existing human health and ecological benchmarks for the 41 CCW constituents to identify the 26 chemicals with benchmarks for constituent screening
- **Constituent Screening**, which compared very conservative estimates of exposure concentrations (e.g., whole waste concentrations, leachate concentrations) to health-based concentration benchmarks to quickly and simply eliminate constituents and exposure pathways that do not require further analysis
- **Full-Scale Analysis**, which used a site-based Monte Carlo analysis to characterize at a national level the risks to human health and ecological receptors from onsite disposal (in landfills and surface impoundments) of CCW constituents that were not eliminated in the screening analysis.

The screening analysis looked at all probable exposure pathways from CCW management in landfills and surface impoundments and identified 21 CCW constituents and 3 exposure scenarios to evaluate in the full-scale analysis (Table ES-1). Exposure scenarios evaluated for people include contaminated groundwater being transported to drinking water wells from a CCW landfill or surface impoundment, and contaminated groundwater discharging into surface water and contaminating a nearby stream or lake where people catch and eat fish. The full-scale analysis also addressed ecological risk in the same waterbodies.

Constituents addressed in the full-scale analysis are listed in Table ES-2 along with the potential exposure pathways identified for full-scale modeling in the screening analysis.

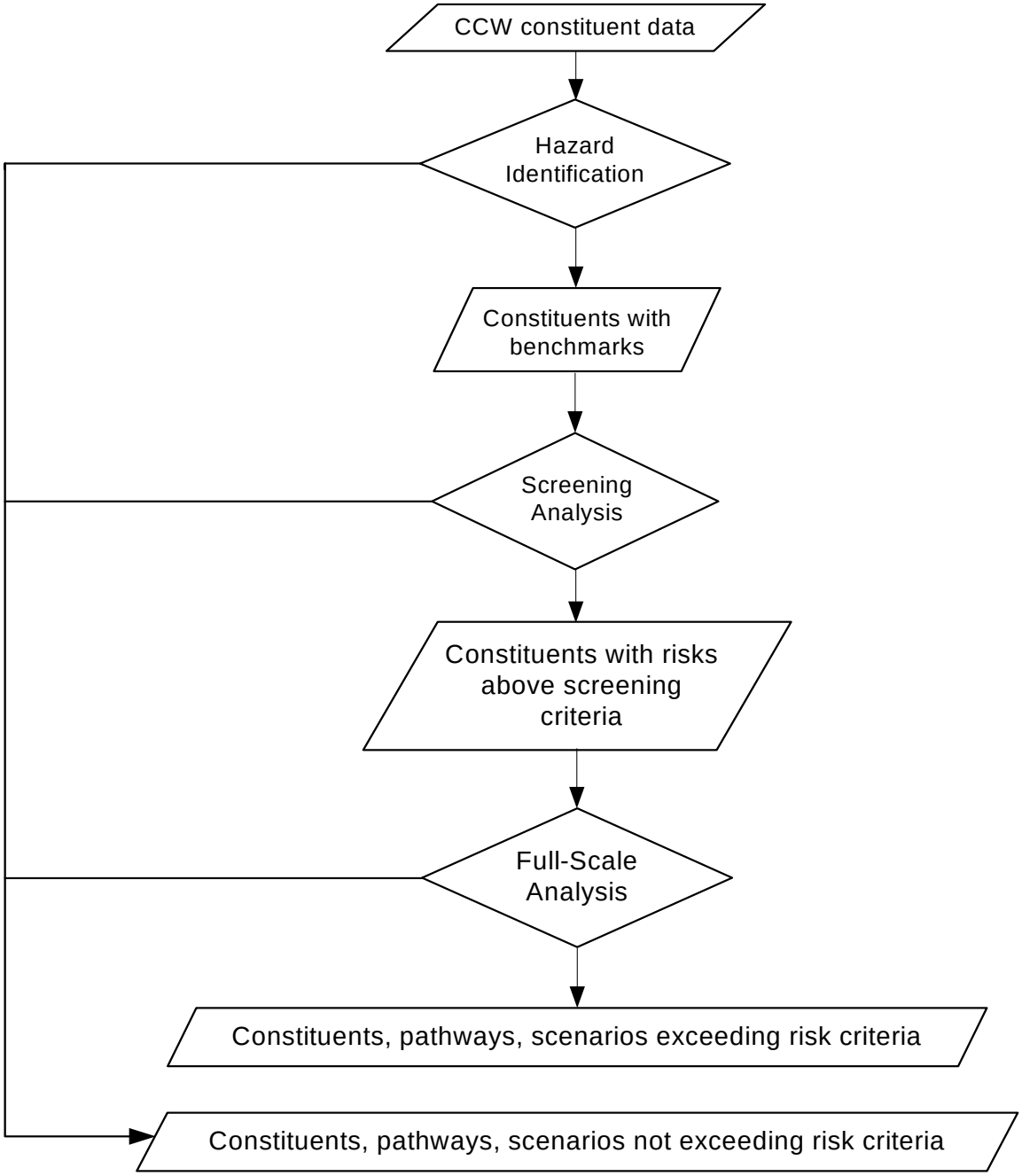


Figure ES-1. Overview of CCW risk assessment.

Table ES-1. Sources, Releases, Exposure Pathways, and Receptors Evaluated in the CCW Risk Assessment

Release Mechanism	Exposure Pathway	Exposure Mechanism	Receptor Type[a]	Screening Result
Landfills				
Leaching	Groundwater-to-drinking-water	Residential well	Resident	Full-scale analysis
	Groundwater-to-surface-water	Stream or lake, uptake by fish; contact with water, sediments	Recreational fisher; aquatic ecosystems	Full-scale analysis
Water erosion	Overland transport to surface water	Stream or lake, uptake by fish; contact with water, sediments	Recreational fisher; aquatic ecosystems	Below screening criteria
	Overland transport to soil	Soil ingestion; uptake from soil by plants, beef, dairy	Subsistence farmer; terrestrial ecosystems	Below screening criteria[b]
Wind erosion	Soil deposition	Soil ingestion; uptake from soil by plants, beef, dairy	Subsistence farmer; terrestrial ecosystems	Below screening criteria
	Fugitive dust	Inhalation	Resident	Below screening criteria
Surface impoundments				
Leaching	Groundwater-to-drinking water	Residential well	Resident	Full-scale analysis
	Groundwater-to-surface water	Stream or lake, uptake by fish; contact with water, sediments	Recreational fisher; ecological receptors	Full-scale analysis

[a] Human receptor types include adults and children.
[b] Except boron for plant toxicity. Also, damage cases indicate soil risks from selenium to terrestrial amphibians (Carlson and Adriano, 1993; Hopkins et al., 2006).

Table ES-2. Screening Analysis Results: CCW Constituents Selected for Full-Scale Analysis[a]

Constituent	Human Health - Drinking Water		Human Health - Surface Water[b]		Ecological Risk - Surface Water	
	LF	SI	LF	SI	LF	SI
Arsenic	•	•	•	•	•	•
Boron	•	•			•	•
Cadmium	•	•	•	•	•	•
Lead	•	•			•	•
Selenium	•	•	•	•	•	•
Thallium	•	nd	•	nd	•	nd
Aluminum					•	•
Antimony	•	nd		nd		nd
Barium					•	•
Cobalt	na	•	na		na	•
Molybdenum	•	•				
Nitrate/Nitrite	•	•				
Chromium	•	•			•	•
Fluoride	•	•				
Manganese		•				
Vanadium	•	•			•	•
Beryllium					•	
Copper					•	•
Nickel		•				•
Silver					•	•
Zinc					•	

LF = landfill.
SI = surface impoundment
nd = nondetect—results are inconclusive because all analyses are nondetects.
na = not available—data were not available for cobalt in CCW landfill leachate.

[a] A mark in a cell indicates that the constituent was above the screening criteria for the indicated pathway and WMU type. Blank cells indicate that the constituent was below the screening criteria for a particular pathway/WMU combination. Risk screening was based on 90th percentile risk concentrations and no attenuation.

[b] Fish consumption pathway.

The full-scale analysis was designed to characterize waste management scenarios based on two waste management options (disposal of CCW onsite in landfills and in surface impoundments). The risk assessment was also used to characterize waste management scenarios based on three liner types (unlined units, clay-lined units, and composite-lined units) and three waste types, as follows:

- **Conventional CCW** (ash and FGD sludge), which includes fly ash, bottom ash, boiler slag, and FGD sludge
- **Codisposed CCWs and coal refuse,**[3] which are more acidic than conventional CCWs due to sulfide minerals in the coal refuse
- **FBC wastes**, which include fly ash and bed ash, and which tend to be more alkaline than conventional CCW because of the limestone mixed in during fluidized bed combustion.

These three waste types and the two waste management options provide a good representation of CCW disposal practices and waste chemistry conditions that affect the release of CCW constituents from WMUs.[4],[5]

The full-scale analysis was implemented using a site-based probabilistic approach that produces a distribution of risks or hazards for each receptor by allowing the values of some of the parameters in the analysis to vary. This approach is ideal for this risk assessment because there are many CCW facilities across the United States, and a site-based approach can capture both the variability in waste management practices at these facilities and the differences in their environmental settings (e.g., hydrogeology, climate, hydrology). This probabilistic approach was implemented through the following steps:

1. Characterize the CCW constituents and waste chemistry, along with the WMUs in which each waste stream may be managed (i.e., the size and liner status of CCW landfills and surface impoundments)
2. Characterize the environmental settings for the sites where CCW landfills and surface impoundments are located (i.e., locations of coal-fired power plants)
3. Identify how contaminants are released from a WMU (i.e., leaching) and transported to human and ecological receptors (i.e., via groundwater and surface water)
4. Predict the fate, transport, and concentration of constituents in groundwater and surface water once they are released to groundwater from the WMUs and travel to receptors at each site
5. Quantify the potential exposure of human and ecological receptors to the contaminant in the environment
6. Estimate the potential risk to each receptor from the exposure and characterize this risk in terms of exposure pathways and health effects.

Based on this approach, we characterized the potential risks associated with the waste disposal scenarios and exposure pathways, including the uncertainties associated with the analysis results.

Results and Conclusions

Risks from clay-lined units are lower than those from unlined units, but 90th percentile risks are still well above the risk criteria for arsenic and thallium for landfills and arsenic, boron, and molybdenum for surface impoundments. Composite liners, as modeled in this assessment, effectively reduce risks from all constituents to below the risk criteria for both landfills and surface impoundments. Although it is likely that today, most new landfills have some type of liner (based on more recent data that were not incorporated into this assessment),

[3] Coal refuse is the waste coal produced from coal handling and preparation operations.

[4] Conventional CCW and codisposed CCW and coal refuse were modeled in landfills and surface impoundments and are the focus of the overall analysis. FBC wastes were treated separately because of limited data on FBC waste management units.

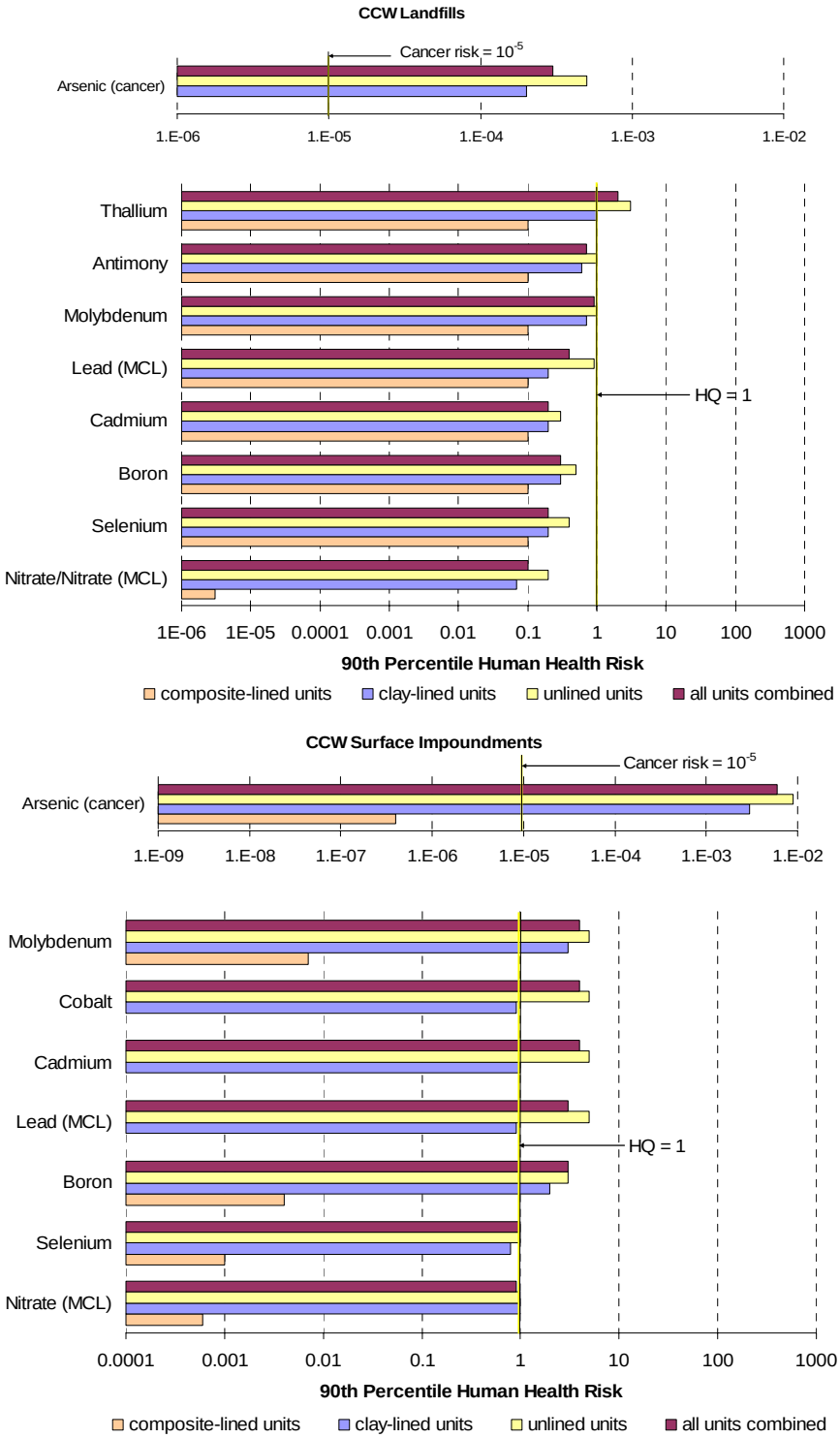
[5] Although different waste chemistries required the separate modeling of conventional CCW and CCW codisposed with coal refuse, the results were combined in this analysis to give an overall picture of the risks from CCW management,

it is not known how many unlined units continue to operate in the United States.

Recent data from a joint DOE/EPA survey suggests that more facilities are lined today than were in the 1995 data set on which this risk assessment is based. This suggests that the risks from CCW may be lower than the results presented in this report, although the older, unlined WMUs represented in this risk assessment may continue to pose potential risks to human health and the environment if they are closed with wastes in place.

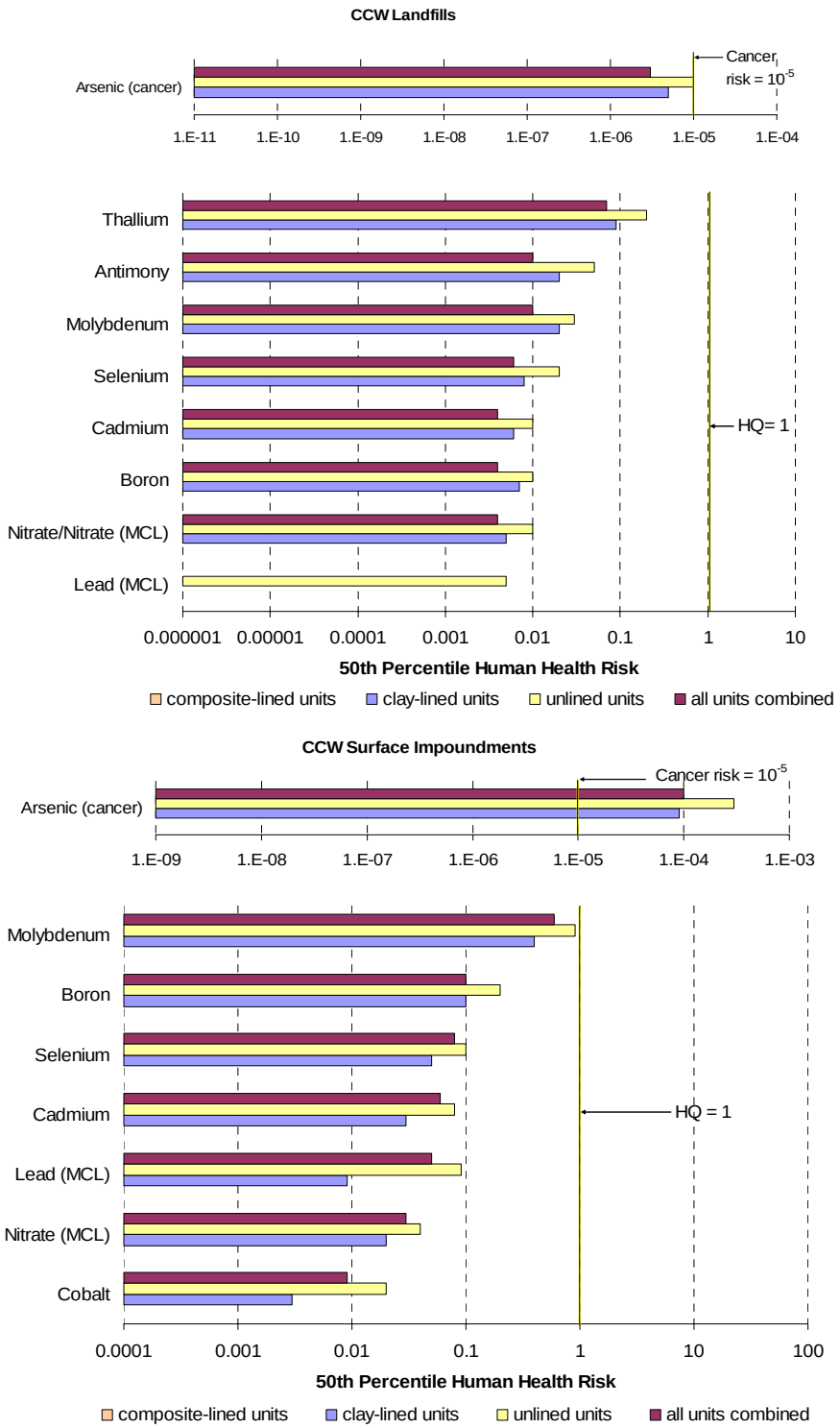
The CCW risk assessment results at the 90th percentile suggest that the management of CCW in landfills and surface impoundments as observed in 1995 for unlined and clay-lined units results in risks greater than the risk criteria of 10^{-5} for excess cancer risk to humans or an HQ greater than 1 for noncancer effects to both human and ecological receptors. Key risk findings include the following:

- 90th and 50th percentile risks for composite-lined units were consistently well below a cancer risk of 10^{-5} and an HQ of 1 for all constituents, waste management scenarios, and exposure pathways modeled in the CCW risk assessment.
- For humans exposed via the groundwater-to-drinking-water pathway (see Figures ES-2 and ES-3), arsenic and thallium show risks to human health above the risk criteria for unlined and clay-lined CCW landfills. Arsenic poses a 90th percentile cancer risk of $5x10^{-4}$ for unlined units and $2x10^{-4}$ for clay-lined units; thallium shows a 90th percentile HQ above 1 for unlined units only. As shown in Figure ES-3, 50th percentile results are at or below risk criteria for all constituents.
- Risks are higher for surface impoundments for the groundwater-to-drinking-water pathway, with a 90th-percentile arsenic cancer risk of $9x10^{-3}$ for unlined units and $3x10^{-3}$ for clay-lined units. For unlined units, 5 additional constituents have noncancer HQs ranging from 3 to 4 for the 90th percentile, including boron, lead, cadmium, cobalt, and molybdenum. Two constituents (boron and molybdenum) have 90th percentile HQs greater than 1 (2 and 3, respectively) for clay-lined surface impoundments. The 50th percentile results are approximately 10-fold greater than the 10^{-5} cancer risk level for arsenic in unlined ($3x10^{-4}$) and clay-lined ($9x10^{-5}$) surface impoundments.
- For humans exposed via the groundwater-to-surface-water (fish consumption) pathway, selenium (HQ = 2) and arsenic (cancer risk = $2x10^{-5}$) show 90th percentile risks for unlined surface impoundments slightly above the risk criteria. All other waste management scenarios and all 50th percentile results show risks at or below the risk criteria for the fish consumption pathway.
- Waste type has little effect on landfill risk results, but surface impoundment risks are higher for codisposed CCW and coal refuse than for conventional CCW.
- Higher risks for surface impoundments than landfills are likely due to a combination of higher waste leachate concentrations, a higher proportion of unlined units, and a higher hydraulic head from 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, the 90th percentile risks for landfills exceed an HQ of 1 for boron and lead. For surface impoundments, risks for the 90th percentile for 6 constituents (boron, lead, arsenic, selenium, cobalt, and barium) exceed an HQ of 1, with boron showing the highest risks (HQ over 2,000). The exceedances for boron and selenium are consistent with reported ecological damage cases, which include impacts to waterbodies through the groundwater-to-surface-water pathway (e.g., Carlson and Adriano, 1993; U.S. EPA, 2007). Only boron exceeds the ecological risk criterion for surface water at the 50th percentile, with an HQ of 4.



A cancer risk of 10^{-5} or an HQ of 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 ES-2. Full-scale 90th percentile risk results for the groundwater-to-drinking-water pathway.



A cancer risk of 10^{-5} or an HQ of 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 ES-3. Full-scale 50th percentile risk results for the groundwater-to-drinking-water pathway.

- For ecological receptors exposed via sediment, 90th percentile risks for lead, arsenic, and cadmium exceeded a HQ of 1 for both landfills (HQs from 2 to 20) and surface impoundments (HQs from 20 to200) probably because these constituents strongly sorb to sediments. No constituents exceed the ecological risk criterion for sediments at the 50th percentile.

Sensitivity analysis results indicate that for more than 75 percent of the scenarios evaluated, the risk assessment model was most sensitive to parameters related to groundwater flow and transport, including WMU infiltration rate, leachate concentration, and aquifer hydraulic conductivity and gradient. For the groundwater-to-surface water pathway, another sensitive parameter is the flowrate of the waterbody into which the contaminated groundwater is discharging. 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 also important.

The multiple uncertainties associated with the CCW risk assessment include scenario uncertainty (i.e., uncertainty about the environmental setting around the plant), uncertainty in human exposure factors (such as exposure duration, body weight, and intake rates), uncertainty in human and ecological toxicity factors and potential cumulative risks, and uncertainty in estimates of fate and transport of waste constituents in the environment. Scenario uncertainty has been minimized by basing the risk assessment on conditions around existing coal-fired power plants around the United States, as observed in 1995. 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 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, as described below:

- **Appropriateness of CCW leachate data.** Although porewater data were available and used for CCW surface impoundments, available data for landfills were mainly Toxicity Characteristic Leaching Procedure (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 cause for CCW damage cases.
- **Limited CCW leachate data.** Because of a high proportion of nondetect values[6] and a limited number of measurements, mercury could not be addressed in the CCW risk assessment for landfills or surface impoundments, and antimony and thallium could not be assessed in surface impoundments. Mercury levels in leachate were measured in EPA's 2006 leaching study and suggest a limited concern for mercury for the CCW leachates investigated, but additional work is needed to extend these results to all CCW disposal facilities.
- **Clean Air Interstate Rule (CAIR) and Clean Air Mercury Rule (CAMR) impacts.** While CAIR and CAMR will reduce air 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 is conducting research on how much total mercury will increase in CCW from the use of mercury controls, as well as how the leachability of mercury and other metals will be impacted. Preliminary results suggest that the impacts on mercury leaching will depend on the mercury control process.
- **Arsenic speciation.** The current model does not speciate metals during subsurface

[6] Nondetect values are measurements where the concentration of a constituent is below the level that the analytical instrument can detect. The actual level could range from zero to just below the detection limit. Nondetects for constituents other than mercury were modeled at one-half the detection limit for this risk analysis.

transport. 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 at the 90th percentile risk level, which is not enough to bring arsenic risks below the risk criteria.

Uncertainties that EPA does not have enough data at this time to evaluate with respect to CCW risk results include the following:

- **Well distance.** Nearest well distances were taken from a survey of municipal solid waste (MSW) landfills because 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 performance.** Liner design and performance for CCW WMUs were based on data and assumptions EPA developed to be appropriate for municipal and nonhazardous industrial waste landfills. EPA believes that CCW landfills should have similar performance characteristics, but does not have quantitative data on CCW WMU liners to verify that.
- **Data gaps for ecological receptors.** Data were insufficient to develop screening levels and quantitative risk estimates for terrestrial amphibians, but EPA acknowledges that damage cases indicate risk to terrestrial amphibians through exposure to selenium (e.g., Hopkins et al., 2006).
- **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 and additive risk.** The impact of exposures to multiple contaminants on 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. The risk assessment also does not add risks across pathways (i.e., risks from drinking water and fish consumption), but EPA does not think that doing so would change the results markedly because the constituents of concern differ between pathways.

EPA recognizes that uncertainties in mercury levels in CCW leachate, both with and without the CAIR/CAMR mercury controls, represent a potentially significant gap in our knowledge of CCW risks.

1.0 Introduction

1.1 Background

The U.S. Environmental Protection Agency (EPA) has evaluated the human health and environmental risks associated with coal combustion waste (CCW) management practices, including disposal in landfills and surface impoundments. In May 2000, EPA determined that regulation as hazardous wastes under Subtitle C of the Resource Conservation and Recovery Act (RCRA) was not warranted for certain CCWs, but that regulation as nonhazardous wastes under RCRA Subtitle D was appropriate. However, EPA did not specify regulatory options at that time. This risk assessment was designed and implemented to help EPA identify and quantify human health and ecological risks that may be associated with current management practices for high-volume CCWs. These wastes are fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) sludge, along with wastes from fluidized-bed combustion (FBC) units and CCWs codisposed with coal refuse. This risk assessment will help EPA develop CCW management options for these high-volume waste streams. Details on EPA's CCW work to date can be found at http://www.epa.gov/epaoswer/other/fossil/index.htm.

Note that the full-scale risk assessment described in this report was mostly conducted in 2003, meaning that the data collection efforts to support the risk assessment were based on the best information available to EPA at that time. As a result, more recent Agency efforts to characterize CCW wastes and management practices, such as the joint EPA and U.S. Department of Energy (DOE) survey of CCW waste management units (WMUs) (U.S. DOE, 2006) and EPA's recent study of CCW chemistries and leaching behavior (U.S. EPA, 2006), were not considered in the main analysis phase of this risk assessment. However, these more recent efforts are discussed as part of the risk characterization, and EPA is currently evaluating how to best incorporate and address the results and findings of these studies in future efforts to address CCW management practices.

The Agency is making the risk analysis document available in the Docket[1] to allow interested parties to submit comments on the analytical methodology, data, and assumptions used in the analysis and to submit additional information for the Agency to consider. In addition, the risk assessment will undergo independent scientific peer review by experts outside EPA following closure of the public comment period. Public comments will be made available to the peer reviewers for their consideration during the review process. The peer review will focus on technical aspects of the analysis, including the construction and implementation of the Monte Carlo analysis, the selection of models to estimate the release of constituents found in CCW from landfills and surface impoundments and their subsequent fate and transport in the environment, and the characterization of risks resulting from potential exposures to human and ecological receptors. As appropriate, EPA will update this analysis based on both public and peer-review comments.

[1] Available at http:www.regulations.gov; docket number EPA-HQ-RCRA-2006-0796.

1.2 Purpose and Scope of the Risk Assessment

The purpose of this risk assessment is to identify CCW constituents, waste types, exposure pathways, and receptors that may produce risks to human and ecological health, and to provide information about those scenarios that EPA can use to develop management options for CCW management.

The scope of this risk assessment is utility CCWs managed onsite at utility power plants. EPA's *Report to Congress: Wastes from the Combustion of Fossil Fuels* (U.S. EPA, 1999a) reports that there are 440 coal-fired utility power plants in the United States. Although these plants are concentrated in the East, they are found in nearly every state, with facility settings ranging from urban to rural. The large volumes of waste generated by these plants are typically managed onsite in landfills and surface impoundments. This risk assessment was designed to develop national human and ecological risk estimates that are representative of onsite CCW management settings throughout the United States.

1.3 Overview of Risk Assessment Methodology

To estimate the risks posed by the onsite management of CCW, this risk assessment estimated the release of CCW constituents from landfills and surface impoundments, the concentrations of these constituents in environmental media surrounding coal-fired utility power plants, and the risks that these concentrations pose to human and ecological receptors.

The size, design, and locations of the onsite CCW landfills and surface impoundments modeled in this risk assessment are based on data from a national survey of utility CCW disposal conducted by the Electric Power Research Institute (EPRI) in 1995 (EPRI, 1997). Data from this survey on facility area, volume, and liner characteristics were used in the CCW risk assessment because they were the most recent and complete data set available at the time the risk assessment was conducted (2003). However, as shown in Table 1-1, the EPA/DOE study conducted since then (U.S. DOE, 2006) shows a much higher proportion of lined facilities than do the 1995 EPRI data.

Table 1-1. Liner Prevalence in EPRI and DOE Surveys

Liner Type	Landfills	Surface Impoundments
1995 EPRI Survey[a] – 181 facilities		
Unlined	40%	68%
Lined (compacted clay or composite [clay and synthetic])	60%	32%
2004 DOE Survey[b] – 56 Facilities		
Unlined	3%	0%
Lined (compacted clay or composite [clay and synthetic])	97%	100%

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

The releases, and hence media concentrations and risk estimates, are based on leaching to groundwater, wind and water erosion, and overland transport. This analysis does not address direct releases to surface water, which are permitted under the National Pollutant Discharge Elimination System (NPDES) of the Clean Water Act. Thus, the estimated media concentrations and risks do not take into account contributions from NPDES-permitted releases, including discharges due to flooding or heavy rainfall.

To evaluate the significance of the estimated risks, the risk criteria adopted for this assessment are

- An estimate of the excess lifetime cancer risk for individuals exposed to carcinogenic (cancer-causing) contaminants of 1 chance in 100,000 (10^{-5} excess cancer risk)[2]
- A measure of safe intake levels to predicted intake levels, a hazard quotient (HQ) greater than 1 for constituents that can produce noncancer human health effects (an HQ of 1 is defined as the ratio of a potential exposure to a constituent to the highest exposure level at which no adverse health effects are likely to occur)
- An HQ greater than 1 for constituents with adverse effects to ecological receptors.

In 1998, EPA conducted a risk assessment for fossil fuel combustion wastes (which include CCWs) to support the May 2000 RCRA regulatory determination (U.S. EPA, 1998a,b). Since then, EPA has added to the waste constituent database that was used in that effort, expanding the number of leachate and total waste analyses for 41 CCW constituents. The CCW risk assessment subjected these waste and leachate constituent concentrations to the tiered risk assessment methodology illustrated in Figure 1-1. This methodology implemented the following steps to assess the human and ecological risk of CCWs:

- **Hazard Identification**, which collected existing human health and ecological benchmarks for the CCW constituents. Only constituents with benchmarks move on to the next step, constituent screening.
- **Constituent Screening**, which compared very conservative estimates of exposure concentrations (e.g., whole waste concentrations, leaching concentrations) to health-based concentration benchmarks to quickly and simply identify constituents and exposure pathways with risks below the screening criteria.
- **Full-Scale Analysis**, which characterized at a national level the human health and ecological risks for constituents in CCW disposed onsite in landfills and surface impoundments using a site-based Monte Carlo risk analysis.

This document focuses on the full-scale Monte Carlo analysis. Constituent screening results are also presented as part of the problem formulation discussion, along with a summary of the screening methodology.[3]

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[2] The typical cancer risk range used by the Office of Solid Waste and Emergency Response is 10^{-4} to 10^{-6}. In hazardous waste listings, the point of departure for listing a waste is 10^{-5}.

[3] Details on the CCW constituent screening analysis can be found in U.S. EPA (2002a).

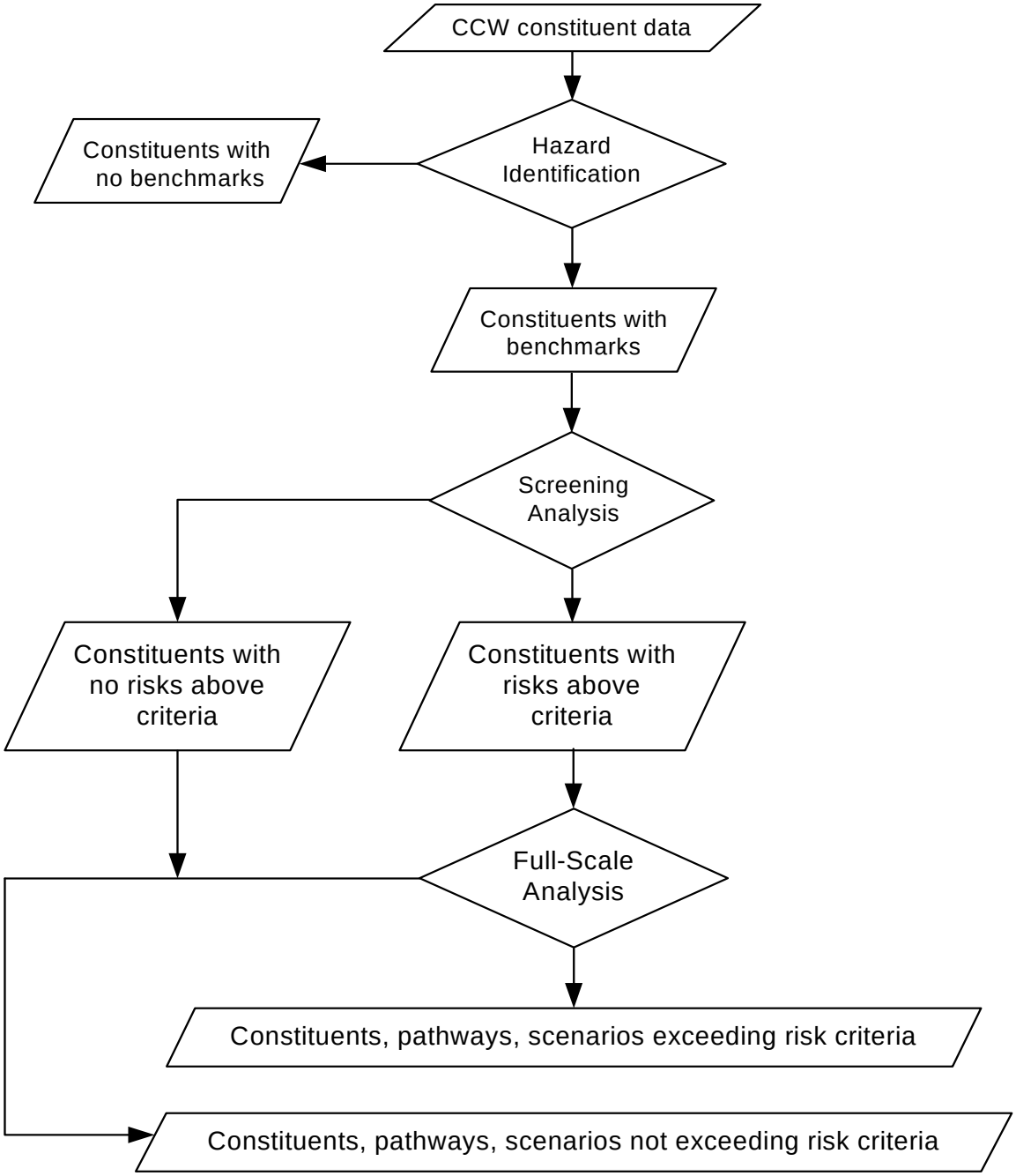


Figure 1-1. Overview of coal combustion waste risk assessment.

1.3.1 Waste Management Scenarios

The full-scale analysis was designed to characterize waste management scenarios based on two waste management options (disposal of CCW onsite in landfills and in surface impoundments) and three waste types, as follows:

- **Conventional CCW**, which includes fly ash, bottom ash, boiler slag, and FGD sludge
- **Codisposed CCWs and coal refuse,**[4] which are more acidic than conventional CCWs due to sulfide minerals in the mill rejects
- **FBC wastes**, which include fly ash and the fluidized bed ash, and which tend to be more alkaline than conventional CCW because of the limestone mixed in during fluidized bed combustion.

Conventional CCW and codisposed CCW and coal refuse are typically disposed of in landfills and surface impoundments that can be lined with clay or composite liners. FBC wastes are only disposed of in landfills in the United States; therefore, surface impoundment disposal was not modeled for FBC waste.

These three waste types, two waste management options, and three liner conditions (unlined, clay-lined, composite-lined) modeled in this analysis provide a good representation of CCW disposal practices and waste chemistry conditions that affect the release of CCW constituents from WMUs.

1.3.2 Approach

The full-scale analysis was implemented using a site-based probabilistic approach that produces a distribution of risks or hazard for each receptor by allowing the values of some of the parameters in the analysis to vary. This approach is ideal for this risk assessment because there are many CCW facilities across the United States, and a site-based approach can capture both the variability in waste management practices at these facilities and the differences in their environmental settings (e.g., hydrogeology, climate, hydrology). This probabilistic approach was implemented through seven primary steps:

Problem Formulation

1. Characterize the CCW constituents and waste chemistry, along with the size and liner status of the WMUs in which each waste stream may be managed
2. Characterize the environmental settings for the sites where CCW landfills and surface impoundments are located

[4] 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 from high amounts of sulfide minerals (like pyrite). 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.”

3. Identify scenarios under which contaminants are released from a WMU and transported to a human receptor

Analysis

4. Predict the fate and transport of constituents in the environment once they are released from the WMUs at each site

5. Quantify the exposure of human and ecological receptors to the contaminant in the environment and the risk associated with this exposure

Risk Characterization

6. Estimate the risk to receptors from the exposure and characterize this risk in terms of exposure pathways, health effects, and uncertainties

7. Identify the waste disposal scenarios and environmental conditions that pose risks to human health or the environment that are above the risk criteria. Evaluate risks at the 50th and 90th percentiles.

1.4 Document Organization

This document is organized into the following sections:

- **Section 2, Problem Formulation,** describes how the framework for the full-scale analysis was developed, including identification of the waste constituents, exposure pathways, and receptors of concern; selection and characterization of waste management practices and sites to model; and development of the conceptual site models for the modeling effort.

- **Section 3, Analysis,** describes the probabilistic modeling framework and the models and methods used to (1) estimate constituent releases from CCW landfills and surface impoundments (source models), (2) model constituent concentrations in the environmental media of concern (groundwater and surface water), (3) calculate exposure, and (4) estimate risk to human and ecological receptors.

- **Section 4, Risk Characterization,** characterizes the human health and environmental risks posed by CCW, including (1) discussion of the methods used to account for variability and uncertainty and (2) identification of the scenarios and conditions that result in risks above the risk criteria. Results are presented as national estimates for CCW landfills and CCW surface impoundments, as well as by waste type and liner status. For risk exceedances, this section identifies the CCW constituents and pathways that exceed the risk criteria, along with any factors (such as liners or facility environmental setting) that might result in higher or lower risk levels. Finally, the risk characterization evaluates the risk results in light of more recent research on CCW waste management practices and the environmental behavior of CCW constituents.

The first three appendices provide detailed information on how wastes, WMUs, and settings were characterized for the risk assessment. Appendix A describes the chemical characteristics of the wastes disposed in the WMUs, including the CCW leachate concentration distributions used. Appendix B describes how EPA characterized the WMUs (landfills and surface impoundments), including surface area, capacities, geometry, and liner status. Appendix C presents the methodologies and data used to characterize the environmental setting at each CCW site, including delineating the site layout and determining the environmental setting (e.g., meteorology, climate, soils, aquifers, and waterbodies).

The remaining appendices provide detailed information on the specific models and data used to calculate risk, including the nonlinear sorption isotherms (Appendix D), the surface water fate and transport and intake equations (Appendix E), the exposure factors (Appendix F), and benchmarks for human health (Appendix G) and ecological risk (Appendix H).

2.0 Problem Formulation

The full-scale CCW risk assessment is intended to evaluate, at a national level, risk to individuals who live near WMUs used for CCW disposal. This section describes how the conceptual framework for the full-scale risk assessment was developed, including

- Constituent selection and screening to identify the CCW constituents, exposure pathways, and receptors to address in this analysis (Section 2.1.1)
- Location and characterization of the CCW landfills and surface impoundments to be modeled as the sources of CCW contaminants in the site-based analysis (Section 2.1.2)
- The conceptual site model used to represent CCW disposal facilities (Section 2.2)
- The general modeling approach and scope (Section 2.3), including data collection, fate and transport modeling to estimate exposure point concentrations, exposure assessment, and the calculation of risks to human and environmental receptors.

2.1 Source Characterization

The main technical aspects of the CCW risk assessment were completed in 2003, and the waste management scenarios modeled in this assessment are based on the best data on industry operations and waste management practices that were available at that time. These data sources include a 1995 industry survey on CCW management practices (the EPRI comanagement survey [EPRI, 1997]) and data collected from a variety of sources before the 2003 risk assessment (e.g., EPA's CCW constituent database). Since 2003, DOE and EPA have completed a survey to characterize CCW waste disposal practices from 1994 to 2004, with a focus on new facilities or facility expansions completed within that same time frame (U.S. DOE, 2006). Although these newer data were not available when this risk assessment was conducted, they are discussed in the risk characterization (Section 4) as an uncertainty with respect to how well the risk assessment represents current WMU liner conditions.

This risk assessment provides a national characterization of waste management scenarios for wastes generated by coal-fired utility power plants. The sources modeled in these scenarios are onsite landfills and surface impoundments, which are the primary means by which CCW is managed in the United States. The characterization of these sources, in terms of their physical dimensions, operating parameters, location, environmental settings, and waste characteristics, is fundamental to the construction of scenarios for modeling. This section describes how the coal combustion waste streams and management practices were characterized (based on the above data sources) and screened to develop the waste disposal scenarios modeled in the full-scale analysis.

2.1.1 Identification of Waste Types, Constituents, and Exposure Pathways

To identify the CCW constituents and exposure pathways to be addressed in this risk assessment, we relied on a database of CCW analyses that EPA had assembled over the past several years to characterize whole waste and waste leachate from CCW disposal sites across the country (see Appendix A). The 2003 CCW constituent database includes all of the CCW characterization data used by EPA in its previous risk assessments, supplemented with additional data collected from public comments, data from EPA Regions and state regulatory agencies, industry submittals, and literature searches up to 2003.

The CCW constituent database represents a significant improvement in the quantity and scope of waste characterization data available from the 1998 EPA risk assessment of CCWs (U.S. EPA, 1998a,b). For example, the constituent data set used for the previous risk assessments (U.S. EPA, 1999a) covered approximately 50 CCW generation and/or disposal sites. With the addition of the supplemental data, the 2003 CCW constituent database covers approximately 140 waste disposal sites.[1] The 2003 database also has broader coverage of the major ion concentrations of CCW leachate (e.g., calcium, sulfate, pH).

2.1.1.1 Waste Types

Comments received by EPA on the previous CCW risk assessment pointed out that the analysis did not adequately consider the impacts of CCW leachate on the geochemistry and mobility of metal constituents in the subsurface. Commenters stated that given the large size of the WMUs and the generally alkaline nature of CCW leachate, it is likely that the leachate affects the geochemistry of the soil and aquifers underlying CCW disposal facilities, which can impact the migration of metals in the subsurface.

To address this concern, EPA statistically evaluated major ion porewater data from the CCW constituent database for the waste streams shown in Table 2-1. Based on this analysis and prevalent comanagement practices, EPA grouped the waste streams into three statistically distinct categories: conventional CCW (ash and FGD sludge) (moderate to high pH); codisposed CCW and coal refuse (low pH); and FBC waste (high pH). As shown in Table 2-1, each of these waste types includes several waste streams that are usually codisposed in landfills or surface impoundments.

Along with the type of WMU (landfill or surface impoundment), the three waste types in Table 2-1 define the basic modeling scenarios to be addressed in the full-scale analysis. To characterize these waste types, the CCW constituent database was queried by waste type to develop the waste concentration data for the constituents and the major ion and pH conditions used to develop waste-type-specific metal sorption isotherms (see Appendix D for a more extensive discussion of the development of CCW waste chemistries and metal sorption isotherms).

[1] Although EPA believes that the 140 waste disposal sites do represent the national variability in CCW characteristics, they are not the same sites as in the EPRI survey. During full-scale modeling, data from the CCW constituent database were assigned to each EPRI site based on the waste types reported in the EPRI survey data.

Table 2-1. Waste Streams in CCW Constituent Database

Waste Type Waste Streams	Number of Sites by Waste Type[a]		
	Landfill Leachate	Surface Impoundment Porewater	Total Waste[b]
Conventional CCW	*97*	*13*	*62*
Ash (not otherwise specified)	43	0	30
Fly ash	61	2	33
Bottom ash and slag	24	3	23
Combined fly and bottom ash	7	4	4
FGD sludge	4	6	5
Codisposed Ash & Coal Refuse	9	5	1
FBC 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] Number of sites by waste type from leachate, porewater, and whole waste data tables in the 2003 CCW constituent database.
[b] Whole waste concentration data.

2.1.1.2 Constituents and Pathways

The CCW constituent database contains data on more than 40 constituents. During the hazard identification step of the CCW risk assessment, constituents of potential concern were identified from this list of constituents by searching EPA and other established sources for human health and ecological benchmarks (e.g., Agency for Toxic Substances and Disease Registry [ATSDR]; see U.S. EPA, 2002a, for a full list of sources). Table 2-2 shows the results of that search for each constituent. Benchmarks were found for 26 chemicals in the constituent database. Constituents without human health or ecological benchmarks were not addressed further in the risk analysis.[2]

To further narrow down the list of constituents, a screening analysis (U.S. EPA, 2002a) was conducted that compared very conservative estimates of exposure concentrations (e.g., whole waste concentrations, leaching concentrations) to health-based concentration benchmarks to quickly, simply, and safely identify constituents and exposure pathways with risks that clearly do not exceed the risk criteria so that these could be eliminated from further analysis. For example, leachate concentrations were compared directly to drinking water standards, which is equivalent to assuming that human receptors are drinking leachate. The technical background document for the CCW screening analysis (U.S. EPA, 2002a) provides further detail on the

[2] The CCW constituents without benchmarks are limited to common elements, ions, and compounds (e.g., iron, magnesium, phosphate, silicon, sulfate, sulfide, calcium, pH, potassium, sodium, carbon, sulfur) that were used to determine overall CCW chemistries modeled in the risk assessment (see Section 3). Although some of these chemicals or parameters (e.g., pH, sulfate, phosphate, chloride) can pose an ecological hazard if concentrations are high enough, they were not addressed in this risk assessment.

Table 2-2. Toxicity Assessment of CCW Constituents

Constituent	CAS ID	HHB[a]	EcoB[b]	Constituent	CAS ID	HHB[a]	EcoB[b]
Metals				***Inorganic Anions***			
Aluminum	7429-90-5	✔	✔	Chloride	16887-00-6		
Antimony	7440-36-0	✔	✔	Cyanide	57-12-5	✔	
Arsenic	7440-38-2	✔[c]	✔	Fluoride	16984-48-8	✔	
Barium	7440-39-3	✔	✔	Nitrate	14797-55-8	✔	
Beryllium	7440-41-7	✔[d]	✔	Nitrite	14797-65-0	✔	
Boron	7440-42-8	✔	✔	Phosphate	14265-44-2		
Cadmium	7440-43-9	✔[d]	✔	Silicon	7631-86-9		
Chromium	7440-47-3	✔[c]	✔	Sulfate	14808-79-8		
Cobalt	7440-48-4	✔	✔	Sulfide	18496-25-8		
Copper	7440-50-8	✔[e]	✔	***Inorganic Cations***			
Iron	7439-89-6			Ammonia	7664-41-7	✔	
Lead	7439-92-1	✔[e]	✔	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		
Thallium	7440-28-0	✔	✔	Total Organic Carbon	none		
Vanadium	7440-62-2	✔	✔	Dissolved Organic Carbon	none		
Zinc	7440-66-6	✔	✔				

[a] HHB = human health effect benchmark
[b] EcoB = ecological benchmark
[c] Known carcinogen (for chromium VI, inhalation only); although arsenic can act as both a carcinogen and a noncarcinogen, the cancer risk exceeds the noncancer risk at any concentration, so we used the more protective cancer benchmark for human health throughout this assessment.
[d] Probable carcinogen
[e] Safe Drinking Water Act Action Level only

screening analysis. As detailed there, the risks for all above-ground pathways analyzed (soil ingestion, inhalation, gardening, beef and dairy, and erosion and overland transport) for human receptors did not exceed the screening criteria for any constituent, so they were not considered any further in the risk assessment. The above-ground pathway risks for ecological receptors also did not exceed the screening criteria except for boron and selenium. Boron, which showed risks above the risk criterion in above-ground pathways due to plant toxicity in the CCW screening analysis, has been shown to be toxic to plants (Carlson and Adriano, 1993). Selenium has shown toxicity to terrestrial amphibians via above-ground pathways (Carlson and Adriano, 1993; Hopkins et al., 2006). Because the risks posed by these CCW constituents to ecological communities via above-ground pathways is well documented in damage cases and field studies (see above references and U.S. EPA, 2007), we did not believe that a full-scale above-ground

pathway analysis was necessary to confirm this conclusion for two constituents. Thus, the full-scale risk assessment did not include any above-ground pathways, only groundwater pathways.

The groundwater-to-drinking-water and groundwater-to-surface-water pathways (human fish consumption and ecological risks) did show risks above the screening criteria for several CCW constituents in the screening analysis. Table 2-3 lists the 21 constituents that had 90th percentile screening analysis groundwater pathway risks greater than a cancer risk of 1 in 100,000 or a noncancer risk with an HQ greater than 1 for human health and 10 for ecological risk.[3] Note that mercury was not addressed in the screening or full-scale analysis because of a very high proportion of nondetects in the CCW constituent database. Similarly, a high number of nondetects (or a very low number of measurements) prevented screening or full-scale analysis for antimony, thallium, and cobalt in surface impoundments. The uncertainties associated with these limited analytical results are discussed in Section 4.4.3.1.

Resources did not allow full-scale modeling to be conducted for all 21 constituents that had 90th percentile risks above the screening criteria. To reduce the number of constituents to be modeled, those constituents were ranked and divided into two groups to focus the full-scale analysis on the CCW constituents that were likely to pose relatively higher risks to human and ecological receptors. The ranking was based on the magnitude of the HQs and the number of HQs exceeding the screening criteria, and was used to select chemicals for full-scale modeling. Constituents with at least one human health HQ greater than 6 or with ecological HQs greater than 100 for both landfills and surface impoundments were modeled. Arsenic, with cancer risks greater than 1 in 1,000, exceeded the cancer risk criterion by a factor of 100 and was also modeled in the full-scale analysis. Constituents with no human health HQs greater than 6 and only one or no ecological HQs greater than 100 were not modeled, but were addressed in a separate analysis using results from the modeled constituents.

Table 2-3 shows the 21 constituents and which of these constituents exceeded the screening criteria and thus were modeled in the full-scale analysis. As shown, 12 constituents were subjected to the full-scale probabilistic risk assessment described in this document. Nine constituents did not exceed the screening criteria and were addressed using risk factors developed from comparing the screening and full-scale results for the modeled constituents, as described in Section 4.1.5 of this document.

2.1.2 Waste Management Scenarios

The full-scale CCW risk assessment models landfills and surface impoundments managing wastes onsite at coal-fired utility power plants. Because EPA selected a site-based modeling approach for the full-scale analysis, it was necessary to locate these disposal sites across the country to provide the spatial foundation for this analysis. It was also necessary to characterize CCW WMUs to define the scope for source modeling.

[3] An HQ of 10 was used for screening ecological risks to account for conservatism of ecological benchmarks and exposure estimates used in the screening analysis (see Section 4.4.3.4).

Table 2-3. Screening Analysis Results: Selection and Prioritization of CCW Constituents for Further Analysis[a]

Constituent	Human Health – Drinking Water		Human Health – Surface Water[b]		Ecological Risk - Surface Water	
	LF HQ (*Cancer Risk*)	SI HQ (*Cancer Risk*)	LF HQ (*Cancer Risk*)	SI HQ (*Cancer Risk*)	LF HQ	SI HQ
Constituents Modeled in Full-scale Assessment						
Carcinogen						
Arsenic[c]	($1.4x10^{-3}$)	($1.8x10^{-2}$)	($2.2x10^{-4}$)	($1.7x10^{-5}$)	49	640
Noncarcinogens						
Boron	4.0	28	-	-	6,600	47,000
Cadmium	3.4	8.9	1.4	3.7	20	52
Lead	16	12	-	-	790	590
Selenium	1.2	2.4	4.7	9.5	35	71
Thallium	21	19	6.3	5.7	-	-
Aluminum	-	-	-	-	120	270
Antimony	22	5.5	-	-	-	-
Barium	-	-	-	-	400	75
Cobalt	-	11	-	-	-	270
Molybdenum	4.2	6.8	-	-	-	-
Nitrate/ Nitrite	- /1.2	60/1.2	-	-	-	-
Constituents Not Modeled in Full-scale Assessment[d]						
Noncarcinogens						
Chromium VI	2.3	4.2	-	-	18	33
Fluoride	1.8	5.2	-	-	-	-
Manganese	1	5.6	-	-	-	-
Vanadium	2.2	2.3	-	-	23	24
Beryllium	-	-	-	-	24	-
Copper	-	-	-	-	16	31
Nickel	-	1.3	-	-	-	14
Silver	-	-	-	-	110	14
Zinc	-	-	-	-	16	-

HQ = screening hazard quotient.
LF = landfill.
SI = surface impoundment.

[a] A dash in a cell indicates that the screening HQ was less than 1 (or 10 for ecological risk), so the risk did not exceed the screening criteria for the indicated pathway.

[b] Fish consumption pathway.

[c] Although arsenic can act as both a carcinogen and a noncarcinogen, the cancer risk exceeds the noncancer risk at any concentration, so we used the more protective cancer benchmark for human health throughout this assessment.

[d] These constituents were addressed using risk attenuation factors developed from full-scale results from modeled constituents (see Section 4.1.5).

Two primary sources of data on these were used to characterize this population:

- 1998 Energy Information Agency (EIA) data on coal-fired power plants, which identifies approximately 300 coal-fired power plants with onsite waste management
- The 1995 EPRI waste comanagement survey (EPRI, 1997), which contains detailed WMU data (i.e., area, capacity, liner status, and waste type) for 177 of those facilities.[4]

Because of the completeness of the WMU data from the EPRI survey, the EPRI data were used to establish the plant locations and WMU data for the full-scale modeling effort for conventional CCW[5] and CCW codisposed with coal refuse.

Although there is a good amount of FBC data in the constituent database (58 sites; see Table 2-1), there were only 3 FBC landfill sites in the EPRI database and 4 additional sites added by EPA for a total of 7 FBC sites with data on onsite WMUs. Because EPA believes that this small sample is not sufficient to represent the universe of FBC disposal units and, if included in the overall analysis, could bias the Monte Carlo results towards the environmental conditions around these few landfill units, FBC waste were addressed separately from the more conventional CCW types in the full-scale analysis and are not included with the conventional and codisposal CCW management scenarios in the overall results. Section 4.1.3 compares the risk results for each of these waste types, including FBC.

Table 2-4 shows how the plants are distributed across the waste type/WMU scenarios modeled in the full-scale analysis. The distribution across the waste type/WMU scenarios, the geographic distribution of these facilities, and the size and liner status of the WMUs were assumed to be representative of all onsite CCW landfills and surface impoundments in the continental United States as of 1995. As mentioned previously, DOE and EPA have conducted a newer survey on CCW disposal facilities (U.S. DOE, 2006), but the scope of this survey was not as comprehensive as the EPRI survey (e.g., WMU areas and capacity data were not collected). EPA does not believe that the number and locations of onsite CCW landfills and surface impoundments has changed significantly since 1995, although liners are more prevalent in the newer facilities (see further discussion in Section 4.4.1). The DOE/EPA report (U.S. DOE, 2006) supports this conclusion.

[4] Note that although there is overlap, the 140-site CCW constituent database described in Appendix A and the EPRI survey used to characterize CCW landfills and surface impoundments were assembled under separate efforts and represent different populations of disposal sites. As described in Section 3.1.3, these data sets were sampled independently during the Monte Carlo analysis, and constituent data were not assigned to particular sites except by waste type.

[5] Fly ash, bottom ash, boiler slag, and FGD sludge.

Table 2-4. Coal Combustion Plants with Onsite CCW WMUs Modeled in the Full-Scale Assessment

Waste Type and Liner Status	Number of Plants in 1995 EPRI Survey[a] with Onsite:		
	Landfills	Surface Impoundments	Either WMU Type[b]
Conventional CCW[c]	71	38	103
unlined	*38*	*24*	*60*
clay-lined	*28*	*10*	*38*
composite-lined	*10*	*5*	*15*
Codisposed CCW and coal refuse	38	65	100
unlined	*20*	*52*	*69*
clay-lined	*10*	*11*	*21*
composite-lined	*9*	*2*	*11*
FBC waste[d]	7	-	7
unlined	*3*		*3*
clay-lined	*3*		*3*
composite-lined	*1*		*1*
All waste types	108	96	181

[a] EPRI (1997); note that some coal combustion plants have one or more onsite WMUs.
[b] Number of coal combustion plants with onsite landfill(s), surface impoundment(s), or both.
[c] Fly ash, bottom ash, boiler slag, and FGD sludge.
[d] Includes 3 EPRI Survey FBC landfills plus 4 additional FBC landfills added by EPA. FBC was treated separately in the full-scale assessment because of the small number of FBC sites.

2.2 Conceptual Model

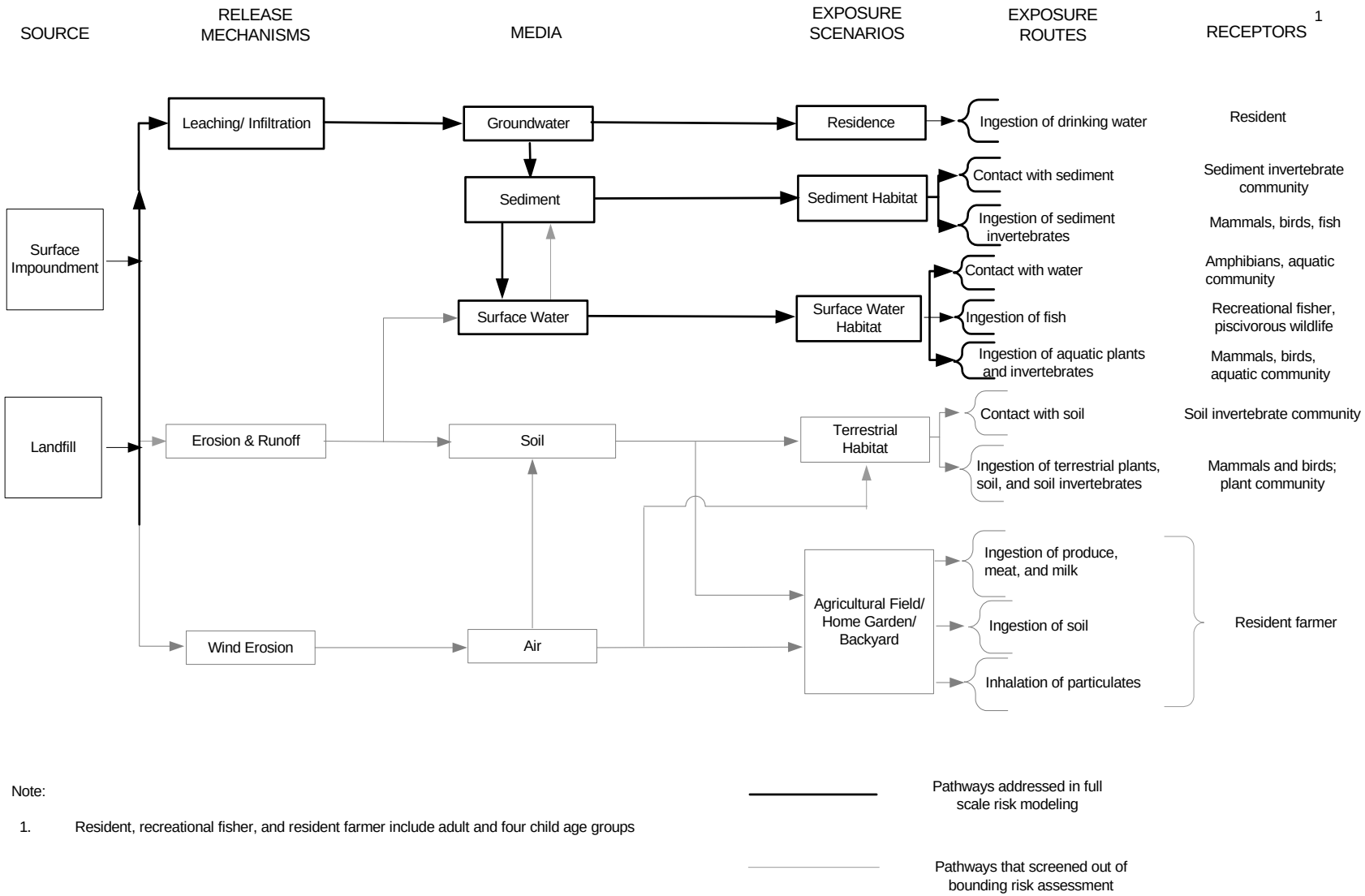
The waste stream/WMU combinations discussed above provide the waste management scenarios to be evaluated in the risk assessment. The full-scale assessment used the EPRI survey data to place these scenarios at actual onsite CCW disposal sites across the country. These sites were used as the basis for a national-scale site-based Monte Carlo assessment of risks posed by the onsite disposal of CCW at utility power plants across the United States.

2.2.1 Conceptual Site Model

Figure 2-1 depicts the conceptual site model for CCW disposal that was the basis for the national CCW risk assessment, including contaminant sources, exposure pathways, and receptors. The CCW conceptual site model includes the following exposure pathways:

Human Health

- Groundwater to drinking water (drinking water ingestion)
- Groundwater to surface water (fish consumption)
- Above-ground pathways, including soil ingestion, inhalation, and consumption of produce, beef, and milk.



Note:

1. Resident, recreational fisher, and resident farmer include adult and four child age groups

Figure 2-1. Conceptual site model of CCW risk assessment.

Ecological Risk

- Groundwater to surface water
- Above-ground soil
- Above-ground contamination of surface water and sediment.

As described in Section 2.1.1, the CCW screening analysis addressed all of these exposure pathways and receptors. Through that screening analysis, risks for all above-ground pathways (shown in gray instead of black in Figure 2-1) fell below the screening criteria and were not considered further in the full-scale risk assessment.[6] This enabled EPA to focus full-scale modeling on groundwater-to-drinking-water and groundwater-to-surface-water exposure pathways (shown in black in Figure 2-1). This groundwater pathway analysis evaluates exposures through drinking water ingestion and surface water contamination from groundwater discharge. For the groundwater-to-surface-water pathway, the analysis assumes that human exposure occurs through the consumption of contaminated fish and that ecological exposure occurs through direct contact with contaminated surface water and sediment or from the consumption of aquatic organisms.

2.2.2 Conceptual Site Layouts

This risk assessment was based on site layouts that are conceptual rather than site-specific. Although we had plant locations and some site-specific data on WMUs, we did not have the exact locations of each WMU or the residential wells surrounding each facility. Therefore, we had to develop conceptual layouts to place receptors around each WMU.

The conceptual site layouts capture possible relationships between a WMU and human and ecological receptors by locating, with respect to the WMU boundary, the geographic features (i.e., receptor wells, waterbodies) that are important for determining human and ecological exposures to chemicals released from CCW landfills and surface impoundments.

Two site layouts were used to model the land use scenarios of most concern for CCW disposal facilities:

- Residential groundwater ingestion scenario
- Recreational fisher and aquatic ecological risk scenario.

Figures 2-2 and 2-3 show these two conceptual site layouts, including WMU boundaries, waterbodies, and residential wells modeled in this analysis. In the conceptual site layouts, the WMU is represented as a square source. The size of the source is determined by the surface area of the WMU (CCW WMU areas were collected from the EPRI comanagement survey, as described in Appendix B). The WMU is assumed to be located at the property line of the facility to which it belongs.

[6] Although the risks from the aboveground screening analysis did exceed the risk criteria for boron and selenium in soil, to streamline the assessment, these compounds were not included in the full ecological assessment.

Adjacent to the WMU is a buffer area within which there is assumed to be no human activity that would present human risk (i.e., there are no residences or waterbodies in the buffer). The buffer area lies between the WMU boundary and the residential well or waterbody, and represents the distance to well or waterbody discharge point modeled by the groundwater model. Each site layout must also be oriented in terms of direction.

Residential Groundwater-to-Drinking-Water Scenario

The residential groundwater-to-drinking-water scenario calculates exposure through residential use of well water as drinking water. In the Monte Carlo analysis, the receptor well is randomly placed up to 1 mile downgradient from the edge of the WMU (this radial well distance is labeled R_{rw} in Figure 2-2), based on a nationwide distribution of nearest downgradient residential wells from Subtitle D municipal landfills (U.S. EPA, 1988a; this distribution is provided in Appendix C). EPA assumed that this distribution is relevant to onsite CCW landfills and surface impoundments at coal-fired utility power plants, but does not have data on typical distances (or the distributions of distances) of domestic drinking water wells from CCW disposal facilities. (The potential impact on the results of this assumption is discussed in Section 4.4.3.3).

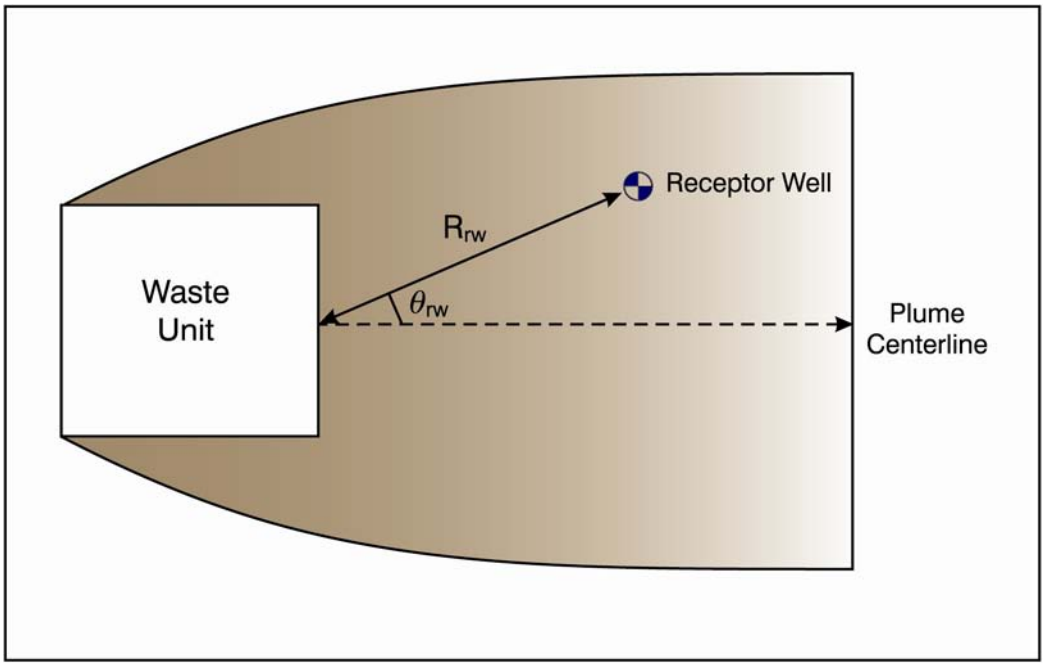


Figure 2-2. Conceptual site layout for residential groundwater ingestion scenario.

The angle off the contaminant plume centerline (θ_{rw} in Figure 2-2) was based on a uniform distribution ranging from 0 to 90°. The depth of the well below the water table was set within the groundwater model based on assumptions that are generally typical of average conditions for surficial aquifers across the United States. These limits are discussed in Section 3.4.3. In this assessment, receptors were always located within the lateral extent of the plume.

The soil and aquifer characteristics needed for the groundwater model were collected using a site-based approach, as described in Appendix C.

Recreational Fisher and Ecological Risk Scenario

The recreational fisher[7] scenario was used to estimate risks to recreational fishers (and their children) who live near the CCW landfills and surface impoundments and catch and consume fish from a waterbody located adjacent to the buffer. Note that the fisher's residence is not the same residence where the residential well is located, and therefore risks are not added across the drinking water and fish consumption pathways.

The waterbody was assumed to be a stream or lake located downgradient from the WMU, beginning where the buffer area ends (see Figure 2-3), and was also used as the most impacted aquatic system for the ecological risk assessment. Waterbody characteristics were determined based on site-specific, regional, or national data (as described in Appendix C), except for stream length, which was determined by the width of the plume as it intersects the waterbody.

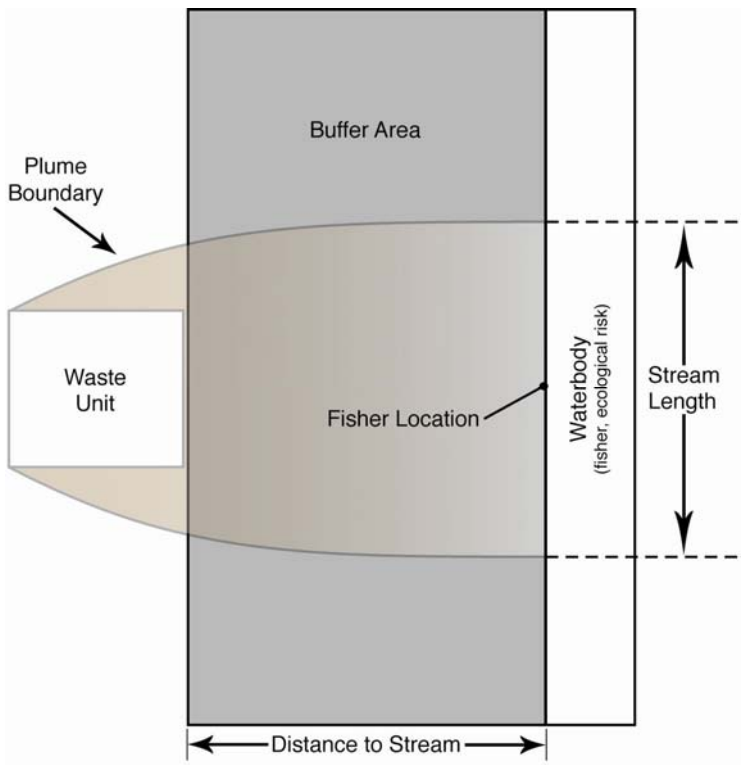


Figure 2-3. Conceptual site layout for residential fisher and aquatic ecological risk scenario.

[7] Only recreational fishers were considered because they represent the reasonable maximum exposed individuals and because the streams, lakes, or rivers that are near CCW plants are not likely to be used by commercial fishing operations.

The downgradient distance to the surface water body was determined from a national distribution developed by measuring this distance (using scaled U.S. Geological Survey [USGS] maps and aerial photographs obtained from the Terraserver Web site [http://terraserver.usa.com/geographic.aspx]) at 59 CCW landfill and surface impoundment sites randomly selected from a larger data set of 204 CCW WMUs, including those modeled in this risk assessment. Appendix C presents that distribution and further details on how the distribution was developed and the sample of 59 facilities used to develop the distribution.

2.3 Analysis Scope and Design

Although the screening analysis identified the potential for risk for a subset of the constituents reported in CCW, the conservative assumptions used precluded an accurate quantitative estimate of these risks. To gain a better understanding of the risks that may be posed by these constituents, EPA conducted a full-scale probabilistic (Monte Carlo) risk assessment to estimate the national distribution of the risks to human health and the environment posed by CCW disposal, and to provide the information needed to assess future management options for these wastes in the context of their risks to human health and the environment. The full-scale CCW Monte Carlo risk assessment was designed to characterize the national CCW risk profile in terms of WMU type, waste type, and constituent, and to use distributions in a probabilistic modeling framework to incorporate variability and uncertainty into the analysis.

The site-based approach used data about waste management practices and environmental conditions at 181 utility CCW disposal sites across the United States.[8] These sites were assumed to represent the universe of CCW onsite waste disposal sites at the time of the EPRI survey (1995) and defined the national framework for the risk assessment. As described in Appendices B and C, site-specific data for the following model inputs were collected for these sites and used in the risk assessment:

- WMU dimensions
- WMU liner status (unlined, clay liner, composite liner)
- Waste type (conventional CCW, CCW codisposed with coal refuse, and FBC wastes)
- Geology (aquifer type)
- Soil texture
- Climate (precipitation, infiltration)
- Surface water type and flow conditions.

One question related to this risk assessment is how CCW facilities may have changed in the decade since the 1995 EPRI survey. Although the DOE/EPA survey does not include all of

[8] These 181 sites include177 sites from the EPRI survey and 4 additional CCW sites added by EPA to better represent FBC waste disposal facilities; see Section 2.1.2.

the data needed to conduct a risk assessment (WMU area and capacity data were not collected), liner conditions were addressed, and by comparing the DOE/EPA survey results to the EPRI data one can assess how liner conditions changed as CCW facilities were built or expanded over the past decade. 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 to 63 percent of the total population of the newly commissioned WMUs.[9] 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. 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. In addition, the available data cannot be used to determine the number of unlined units that continue to operate in the United States.

Because site-specific data were not readily available for depth to groundwater or receptor location (i.e., distances to nearest drinking water well and surface waterbody), national distributions for those inputs taken from a national hydrogeologic database (Newell et al., 1989 and 1990) developed to support EPA's national groundwater risk assessments were used in the Monte Carlo analysis to characterize the national variability of receptor distances (see Appendix C). This enabled EPA to assess the importance of those variables for the national risk distribution for individuals with reasonable maximum exposure to CCW.

The full-scale assessment was conducted using several modeling components: (1) EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP; U.S. EPA, 1997a) groundwater model, (2) a simple steady-state surface water and aquatic food web model, and (3) a multipathway exposure and risk modeling system.

2.3.1 Data Collection

For the sites representing each WMU and waste type combination selected for analysis, the Monte Carlo analysis begins with input files that contain, for each Monte Carlo realization, the following site-based variables:

- WMU area, depth, and capacity
- WMU liner status

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

- Soil texture (for vadose zone properties and infiltration rates)
- Soil pH and organic carbon
- Aquifer type
- Groundwater temperature
- Climate center (for infiltration rates)
- USGS Hydrologic Region (for surface water quality data)
- Surface water flows.

CCW constituent data in the CCW constituent database were used as a national empirical distribution of the concentrations of the constituents of concern in CCW landfill leachate and surface impoundment porewater. Like the WMU database, the CCW constituent data include WMU type and waste type, which enabled constituent concentrations to be assigned to the 181 CCW sites by waste type and WMU type. The CCW constituent database was also used to assign (by waste type) the high, medium, and low leachate pH and ionic strength conditions needed to select the appropriate subsurface sorption isotherms for each model run (see Appendix D).

National distributions were used to populate the following variables by model run:

- Distance to nearest drinking water well
- Distance to nearest surface waterbody
- Aquifer depth, thickness, gradient, and hydraulic conductivity (based on site-specific hydrogeologic setting)
- Soil hydrologic properties (based on site-specific soil type).

The data sources used to develop national distributions for these variables are described in Appendix C. Human exposure factors, such as exposure duration and drinking water and fish consumption rates, were also based on national distributions, which are provided in Appendix F.

2.3.2 Model Implementation

As a first step in the modeling process, the groundwater model (EPACMTP) reads the site-based data files to estimate the following for each model run:

- Drinking water well peak concentration
- Time to drinking water peak concentration
- Peak surface water contaminant flux
- Time to peak surface water contaminant flux.

The groundwater model is run until contaminant concentrations at the receptor point return to zero after the concentration peak or for the maximum simulation time of 10,000 years, whichever comes first.

Groundwater model results are passed to the multimedia modeling system to estimate surface water and sediment concentrations and to calculate human and ecological exposure and risk. Additional inputs sent to the model at this stage include

- Site-based surface waterbody type, dimensions, flows, pH, and total suspended solids (TSS) concentration
- Chemical-specific fish bioconcentration factors (BCFs)
- Human exposure factors (from national distributions)
- Human and ecological health benchmarks.

For human health, the multimedia modeling system calculates risk from drinking water ingestion and fish consumption for each realization. For ecological risk, the model uses surface water and sediment concentrations along with ecological benchmarks to estimate the risks to ecological receptors.

2.3.3 Exposure Assessment

Table 2-5 lists the human and ecological receptors considered in the CCW risk assessment, along with the specific exposure pathways that apply to each receptor. All of the receptors that EPA considered were assumed to live offsite, at a location near the WMU.

Table 2-5. Receptors and Exposure Pathways Addressed in the Full-Scale CCW Assessment

Receptor	Ingestion of Drinking Water	Fish Consumption	Direct Contact with Surface Water and Sediment	Ingestion of Aquatic Organisms
Human Receptors				
Adult resident	✔			
Child resident	✔			
Adult recreational fisher		✔		
Child recreational fisher		✔		
Ecological Receptors				
Aquatic and sediment organisms			✔	
Mammals and birds				✔

For human receptors, the exposure assessment estimates the dose to an individual receptor by combining modeled CCW constituent concentrations in drinking water or fish with intake rates for adult and child receptors. The full-scale CCW risk assessment considered

exposures due to chemicals leaching from WMUs and contaminating groundwater. The groundwater exposures include drinking water ingestion and consumption of recreationally caught contaminated fish from surface waterbodies affected by contaminated groundwater. For the groundwater-to-drinking-water pathway, it was conservatively assumed that well water was the only source of drinking water (although some households may drink bottled or treated water or may drink water outside the home, e.g., at work or at school).

For ecological receptors, exposure assumptions are incorporated into the development of ecological benchmarks (see Appendix H), which are surface water and sediment concentrations corresponding to an HQ of 1.

The time period for the exposure assessment is defined by the peak concentration in the media of concern and the exposure duration. For human receptors, annual average media concentrations were averaged over the randomly selected exposure duration around the peak concentration for each run. To protect against chronic effects to ecological receptors, we consider the exposure duration over a significant portion of the receptor's lifetime, and we believe that one year is the appropriate period of time for that. To be protective, we use the highest (peak) annual average concentration to estimate ecological exposure and risk.

2.3.4 Risk Estimation

Risk was estimated using several risk endpoints as particular measures of human health risk or ecological hazard. A risk endpoint is a specific type of risk estimate (e.g., an individual's excess cancer risk) that is used as the metric for a given risk category. The CCW risk assessment evaluated cancer and noncancer endpoints for humans and noncancer endpoints for ecological receptors. For human risk, the availability of toxicological benchmarks for cancer and noncancer effects determined which endpoints were evaluated for each constituent.

EPA used two risk endpoints to characterize risk for the human receptors and a single risk endpoint, total HQ, to characterize risk for ecological receptors. These endpoints are discussed in Section 3.8; in addition, uncertainty related to these endpoints is discussed in Section 4.4.3.4.

From the distribution of risks for each risk endpoint generated by the Monte Carlo analysis, the 50th and 90th percentile risks were selected and compared to the risk criteria of 1 in 100,000 excess cancers and an HQ greater than 1 for noncarcinogens. An HQ greater than 1 for was also used for the ecological risk criterion in the full-scale risk assessment.

3.0 Analysis

The full-scale analysis evaluates risks from CCWs disposed of in landfills and surface impoundments located onsite at coal-fired utility power plants across the United States based primarily on data collected in 1995 by EPRI (1997).[1] Chemical constituents found in CCW can be released from these WMUs into the surrounding environment by various mechanisms. Releases to the atmosphere and by erosion and overland transport did not pose risks above the screening criteria in the screening analysis; therefore, these were not assessed in the full-scale analysis. Instead, the full-scale analysis focused on groundwater pathways, which exceeded the risk criteria for some constituents in the screening analysis. Leachate forms in both landfills and surface impoundments, migrates from the WMU through soil to groundwater, and is transported in groundwater to drinking water wells (groundwater-to-drinking-water pathway) and into surface waterbodies near the WMU (groundwater-to-surface-water pathway). These are the groundwater pathways evaluated in the full-scale CCW risk assessment.

For the full-scale analysis, EPA used computer-based models and sets of equations to estimate the risk to human health and the environment from current CCW disposal practices.[2] These models include

- **Source** models that simulate the release of CCW constituents in leachate from landfills and surface impoundments[3]
- **Fate and transport** models that estimate contaminant concentrations in groundwater and surface water
- **Exposure** models that estimate daily contaminant doses for humans and ecological receptors exposed to CCW constituents in groundwater and surface water
- **Risk** models that calculate risks to humans and ecological receptors.

This section describes the models and equations used to calculate exposure point concentrations and risk. Section 3.1 provides the overall structure for the analysis, including the spatial and temporal framework and the probabilistic (Monte Carlo) framework for the model runs. Sections 3.2 and 3.3 describe the landfill and surface impoundment source models used to predict environmental releases of constituents from CCW. Sections 3.4 and 3.5 describe the fate and transport modeling used to predict contaminant concentrations in groundwater and surface

[1] The selection and characterization of these CCW WMUs are described in more detail in Appendix B.

[2] As discussed in Section 2, the 1995 EPRI survey data is assumed to represent current CCW management practices. However, new data from a more recent DOE/EPA survey suggest that liners may be more prevalent in new and expanded units built since 1994. Section 4 discusses implications of this uncertainty on the risk assessment results.

[3] EPA used source-term models integrated into EPACMTP to estimate environmental releases of constituents in leachate from landfills and surface impoundments.

water. Section 3.6 describes the human exposure calculations. Section 3.7 describes the health benchmarks used to develop human and ecological risk estimates, and Section 3.8 describes how these risks were calculated for human and ecological receptors.

Supporting detail can be found in the following appendices:

- **Appendix A, Constituent Data**, provides the CCW constituent concentrations used and describes how they were collected and processed
- **Appendix B, Waste Management Unit Data**, describes the location and characteristics of each landfill and surface impoundment modeled and describes how the source model input parameter values were collected
- **Appendix C, Site Data**, describes how environmental data around each CCW waste disposal site were collected to provide inputs for the groundwater and surface water modeling
- **Appendix D, MINTEQA2 Nonlinear Sorption Isotherms**, describes the development and application of the CCW-specific MINTEQ metal sorption isotherms used to model fate and transport in soils and groundwater
- **Appendix E, Surface Water, Fish Concentration, and Contaminant Intake Equations**, documents the algorithms used to calculate surface water concentrations, fish concentrations, and drinking water and fish intake rates
- **Appendix F, Human Exposure Factors**, documents the human exposure parameters and equations
- **Appendix G, Human Health Benchmarks**, describes how the human toxicity benchmarks were selected and developed
- **Appendix H, Ecological Benchmarks**, describes how the ecological toxicity benchmarks were selected and developed.

3.1 General Modeling Approach

This section describes the framework, general assumptions, and constraints for the full-scale probabilistic analysis. Section 3.1.1 describes the temporal and spatial framework. Section 3.1.2 describes the probabilistic framework, and Section 3.1.3 describes how the assessment was implemented within the probabilistic framework.

3.1.1 Temporal and Spatial Framework

The spatial framework for the analysis was determined by the geographic distribution of CCW facilities modeled and by the site layout assumed as the conceptual site model for risk assessment. As described in Section 2.1.2, the geographic distribution of landfills and surface impoundments managing wastes onsite at coal-fired utility power plants was determined from

the 177 sites in the 1995 EPRI survey of the onsite management of CCW (EPRI, 1997). The assessment assumes that these 177 sites and their locations are representative of the approximately 300 coal-fired power plants identified by EIA data as having onsite waste management of conventional CCW and CCW codisposed with coal refuse throughout the United States. For FBC wastes, these 177 sites include only 3 FBC landfills. EPA was able to add 4 additional FBC landfill sites to better represent FBC waste management, for an overall total of 181 sites in this analysis.

The conceptual site layouts applied to each of the sites are described and pictured in Section 2.2.2. Two site layouts were used to define the relationship between a landfill or surface impoundment and (1) a drinking water well (for human risk via the groundwater-to-drinking-water pathway) and (2) a surface water body (for human and ecological risk via the groundwater-to-surface-water pathway). In each case, the receptor point (well or waterbody) was assumed to lie within the boundaries of the groundwater contaminant plume. The distance from the edge of the WMU to the well or waterbody was varied for each model run based on national distributions, with well distance taken from a national distribution for Subtitle D municipal landfills (U.S. EPA, 1988a) and distance to surface water taken from a set of measured distances for CCW landfills and surface impoundments developed for this assessment. Appendix C presents additional details on these distributions.

The temporal framework was mainly defined by the time of travel from the modeled WMU to the well or waterbody, which can be up to one mile away from the edge of the unit, and the exposure duration over which risks were calculated. The subsurface migration of some CCW constituents (e.g., lead) may be very slow; therefore, it may take a long time for the contaminant plume to reach the receptor well or nearest waterbody, and the maximum concentration may not occur until a very long time after the WMU ceases operations. This time delay may be on the order of thousands of years. To avoid excessive model run time while not missing significant risk at the receptor point, the groundwater model was run until the observed groundwater concentration of a contaminant at the receptor point dropped below a minimum concentration (10^{-16} mg/L) or until the model had been run for a time period of 10,000 years. The minimum concentration used for all fate and transport simulations (10^{-16} mg/L) is at least a million times below any risk- or health-based criteria.

For the groundwater-to-drinking-water pathway (human health risk), risks were calculated based on a maximum time-averaged concentration around the peak concentration at each receptor well. The exposure duration (which varies from 1 to 50 years)[4] was applied around the peak drinking well concentration to obtain the maximum time-averaged concentration.

For the groundwater-to-surface-water pathway, the groundwater model produces surface water contaminant loads (based on groundwater concentration and flow) for a stream that penetrates the aquifer. Because the surface water model is a steady-state model, there is no temporal component to it and the receptor is exposed to the same concentration over the entire exposure duration. For human health risk, the loadings from groundwater to surface water were averaged over the exposure duration, bracketing the time of the peak groundwater concentration.

[4] Distributions of exposure duration and other exposure variables were obtained from the *Exposure Factors Handbook* (U.S. EPA, 1997c,d,e)

The exposure duration for sensitive ecological receptors is generally a year or less; therefore, for ecological risk, a single peak annual average surface water concentration was used.

For all scenarios, if the groundwater model predicted that the maximum groundwater concentration had not yet occurred after 10,000 years, the actual groundwater concentration at 10,000 years was used in the exposure calculations instead of a maximum time-weighted average concentration around the peak.

3.1.2 Probabilistic Approach

The full-scale analysis evaluates risk in a probabilistic manner and is based on a Monte Carlo simulation that produces a distribution of exposures and risks. The general Monte Carlo approach is shown in Figure 3-1. The foundation of the Monte Carlo simulation is the source data derived from the EPRI survey. These were combined with data from the national CCW constituent database to conduct a Monte Carlo simulation of 10,000 iterations per waste type/WMU type/constituent combination.

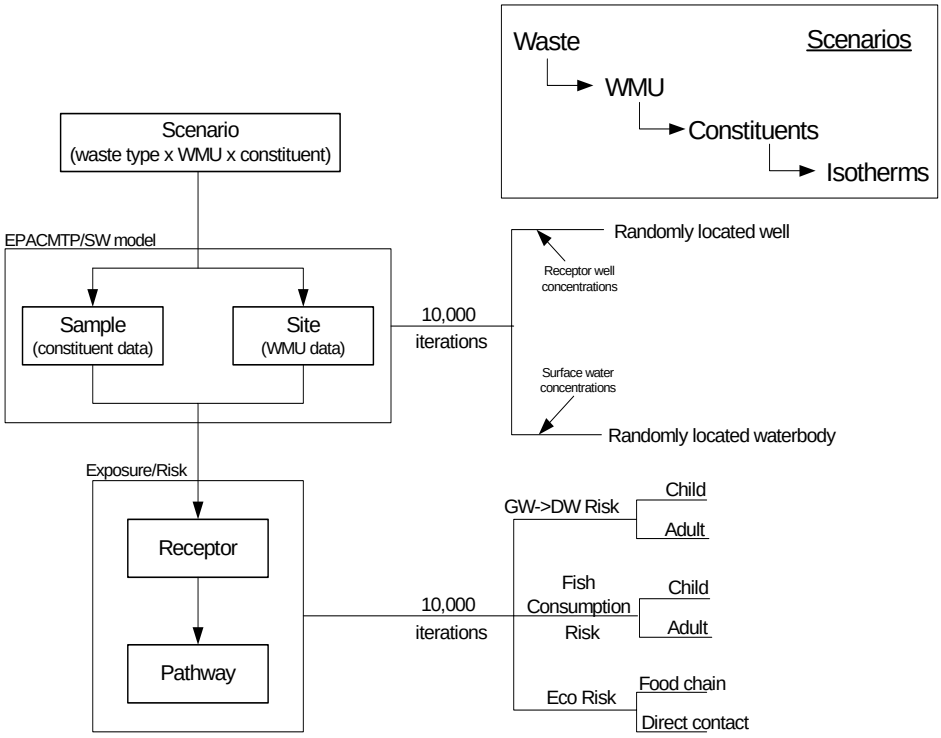


Figure 3-1. Overview of the Monte Carlo approach.

The detailed looping structure for the Monte Carlo analysis is shown in Figure 3-2. For each waste type/WMU combination, two separate loops are run. The first loop (shown with dashed lines in Figure 3-2) prepares a set of input files containing 10,000 sets of WMU and site data (as described in Section 3.1.3). The second loop (shown with solid lines in Figure 3-2) uses those input files to run 10,000 iterations of the source, fate and transport, exposure, and risk models for each constituent.

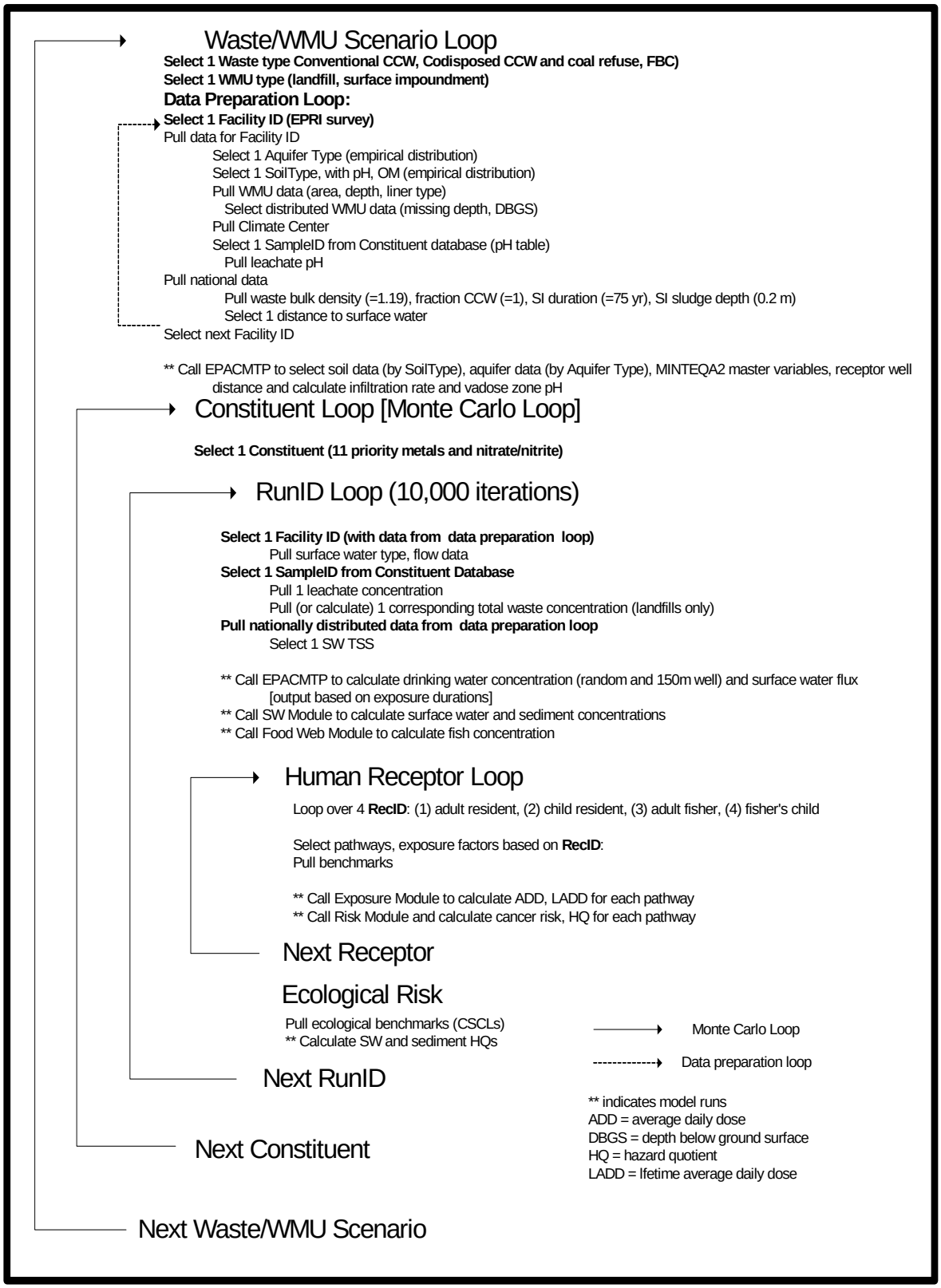


Figure 3-2. Monte Carlo looping structure.

3.1.3 Implementation of Probabilistic Approach

Table 3-1 lists the five waste disposal scenarios addressed in the full-scale analysis. FBC waste landfills were modeled and treated as a separate scenario in the analysis because of the limited number (7) of FBC landfill sites. Each waste disposal scenario modeled in the full-scale assessment included unlined, clay-lined, and composite-lined WMUs. Additional detail on these scenarios can be found in Section 2-1 and Appendix A.

Table 3-1. CCW Waste Management Scenarios Modeled in Full-Scale Assessment

WMU Type	Waste Type
Conventional CCW and CCW Codisposed with Coal Refuse (main analysis)	
Landfill	Conventional CCW (fly ash, bottom ash, boiler slag, FGD sludge)
Landfill	Codisposed CCW and coal refuse
Surface impoundment	Conventional CCW
Surface impoundment	Codisposed CCW and coal refuse
FBC Waste (separate analysis)	
Landfill	FBC waste (fly ash, bottom ash, bed ash)

To capture the national variation in waste management practices for the Monte Carlo analysis, an input database was created with approximately 10,000 iterations for each of the waste type/WMU combinations. This input database provided the source data for 10,000 iterations of the source modeling and the fate and transport modeling. Figure 3-3 provides an overview of the process used to compile these data, which were organized into source data files. As shown in Figure 3-3, seven tasks, some parallel and some sequential, were required to construct these data files, one file for each waste management scenario.

Constructing the source data files for use in the probabilistic analysis involved first developing a 10,000-record data file for each waste type-WMU scenario. This was accomplished by selecting the landfills and surface impoundments from the EPRI survey data that manage each type of waste. Within a scenario, a list of the EPRI plants with that WMU type and waste type was repeated to produce around 10,000 records. For each record, site-based, regional, and national inputs were randomly selected from distributions developed to characterize the regional or national variability in these inputs. Each record in the source data files was identified by a model run identification number (RunID).

The EPRI survey provided most of the WMU data needed, including area, capacity, liner type, and waste type. Additional data were collected to characterize the height and depth below ground surface of typical CCW landfills and surface impoundments (see Appendix B).

The environmental setting in which waste disposal occurs was characterized based on the location of the 181 power plants used in the full-scale analysis. These locations were used to characterize climate, soils, aquifers, and surface water bodies at each site as follows (see Appendix C for details):

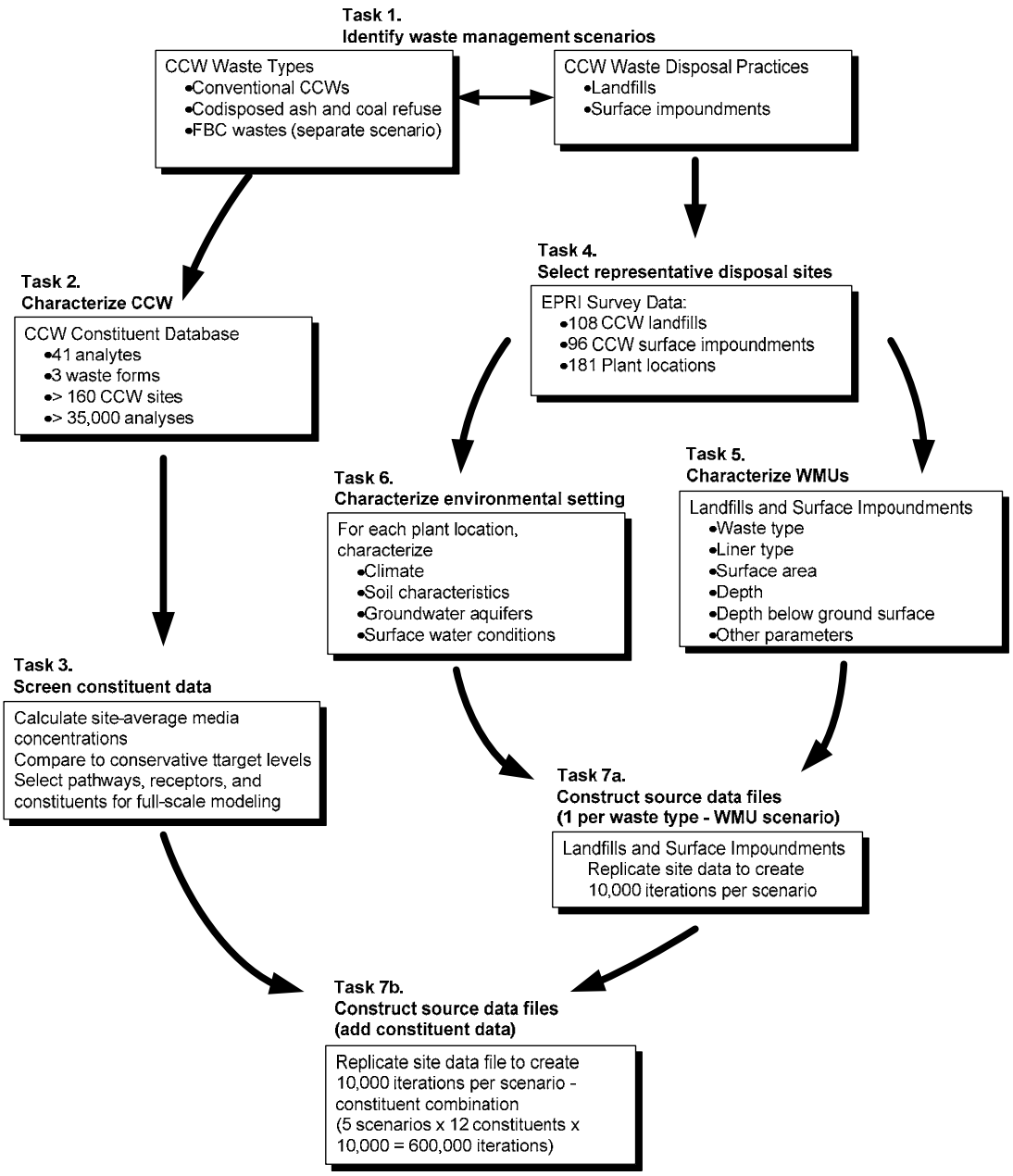


Figure 3-3. Process used to construct the Monte Carlo input database.

- Climatic data, including annual precipitation, temperature, and windspeed, were collected by assigning each site to a nearby meteorologic station.
- Soil and aquifer type were collected within a 5-km radius of each site to account for locational uncertainty for the WMUs.
- Surface water type and flows were collected using a geographic information system (GIS) to identify the nearest stream and by matching plants to the Permit Compliance

System (PCS) database to get the stream segment for each plant's NPDES discharge point.

These site-based data were supplemented with regional data on surface water quality and with national distributions of receptor distances (i.e., distance to drinking water well and distance to nearest surface waterbody). Appendix C describes the site-based approach and data sources used for these site-specific, regional, and national-scale data collection efforts.

The five 10,000-record scenario-specific source data files were then combined with the CCW constituent data for each constituent in the appropriate waste type to develop the final source data files for each scenario. With 12 constituents modeled for most scenarios, this resulted in over 600,000 records in the final input data set.

3.2 Landfill Model

Releases from landfills were modeled using a landfill source-term model contained in EPACMTP. EPA has used EPACMTP and its predecessor models for almost 20 years to conduct groundwater risk assessments in support of regulations for land disposal of hazardous and nonhazardous wastes. In that context, EPACMTP has undergone numerous peer reviews, including multiple reviews by EPA's Science Advisory Board (SAB). Each of these reviews has supported and approved the use of this model for developing national regulations and guidance, including verification that the model and model code are scientifically sound and properly executed. Some of the more important reviews include

- A 1989 review by SAB of the component saturated zone (groundwater) model used in EPACMTP
- A 1993 review by EPA's Office of Research and Development (ORD) of EPACMTP for potential Hazardous Waste Identification Rule applications, which resulted in a number of improvements in the computational modules of EPACMTP
- A 1994 consultation with SAB on the use of EPACMTP for determination of dilution-attenuation factors for EPA's *Soil Screening Guidance*
- A 1994 review by expert modelers Dr. Fred Molz (Auburn University) and Mr. Chris Neville (SS Papadopoulos & Associates), who verified that the mathematical formulation of the model and the code verification testing are scientifically sound
- The peer-reviewed publication of EPACMTP in the *Journal of Contaminant Hydrology* (Kool et al., 1994)
- An in-depth review by SAB related to the use of EPACMTP in the proposed/draft 1995 Hazardous Waste Identification Rule (U.S. EPA, 1995)
- A 1999 peer review by leading modelers of the implementation of EPACMTP in EPA's multimedia, multiple exposure pathway, multiple receptor risk assessment (3MRA) model (U.S. EPA, 1999c)

- A 2003 SAB review of the 3MRA implementation of EPACMTP (SAB, 2004).

An overview and statement of assumptions for the landfill model is presented here, followed by a listing of inputs to the landfill source-term model and a brief discussion of the output generated by the model.

3.2.1 Conceptual Model

The landfill model treats a landfill as a permanent WMU with a rectangular footprint and a uniform depth (see Figure 3-4). If only the area is known (which is the case for the CCW landfills), the landfill source-term model assumes a square footprint. The model assumes that the landfill is filled with waste during the unit's operational life and that upon closure of the landfill, the waste is left in place and a final soil cover is installed.

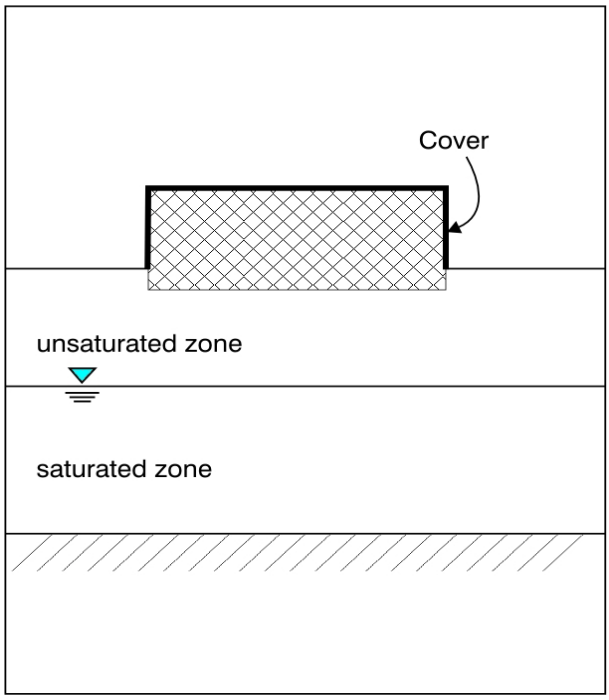


Figure 3-4. Conceptualization of a landfill in the landfill source-term model.

Three liner scenarios were modeled: a no-liner (unlined) scenario, a compacted clay liner, and a composite liner that combines a high-density polyethylene (HDPE) membrane with either geosynthetic or natural clays.

In the unlined scenario, 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.

In the clay liner scenario, 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