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Interim Findings on the Status of Visibility Research

Office of Research and Development
Office of Air and Radiation

U.S. Environmental Protection Agency

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I. Introduction

I.A. Purpose

This report has been prepared in response to the provisions of §169B(a) of the Clean Air Act (CAA)[a] that call for the Administrator of the U.S. Environmental Protection Agency (EPA) to produce interim findings of available visibility related research and information:

> (1) The Administrator, in conjunction with the National Park Service and other appropriate Federal agencies, shall conduct research to identify and evaluate sources and source regions of both visibility impairment and regions that provide predominantly clean air in class I areas.[b] A total of $8,000,000 per year for 5 years is authorized to be appropriated for the Environmental Protection Agency and the other Federal agencies to conduct this research. The research shall include-
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> > (A) expansion of current visibility related monitoring in class I areas;
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> > (B) assessment of current sources of visibility impairing pollution and clean air corridors;
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> > (C) adaptation of regional air quality models for the assessment of visibility;
> >
> > (D) studies of atmospheric chemistry and physics of visibility.
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> (2) Based on the findings available from the research required in subsection (a)(1) of this section as well as other available scientific and technical data, studies, and other available information pertaining to visibility source-receptor relationships, the Administrator shall conduct an assessment and evaluation that identifies, to the extent possible, sources and source regions of visibility impairment including natural sources as well as source regions of clear air for class I areas. The Administrator shall produce interim findings from this study within 3 years after enactment of the Clean Air Act Amendments of 1990.

The purpose of this interim report is to summarize the results of visibility research published since 1990, both federal and non-federal, that relate to the research objectives stated in §169B(a) of the CAA. Evaluation and assessment of the results is premature at this time. Thus, the report describes or recounts the research and does not address its merits. Moreover, the report does not make EPA policy determinations about visibility protection.

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[a]Section 816 of the 1990 Clean Air Act Amendments (CAAA) added Section 169B to the Clean Air Act (CAA or Act). See Pub. Law No. 101-549, 104 Stat. 2399, 2695-2697. The Clean Air Act is codified, as amended, at 42 U.S.C. §§7401-7671q.

[b]Mandatory class I areas (certain large national parks, wilderness areas, etc.) where visibility is an important value and associated integral vistas are identified at 40 CFR Part 81, Subpart D.

I.B. Report Structure

Following this introductory Section (I), Section II summarizes the findings of four major visibility related reports published since 1990:

- National Academy of Sciences Report 1993, "Protecting Visibility in National Parks and Wilderness Areas"
- IMPROVE (Interagency Monitoring of Protected Visual Environments) 1993 Report
- 1992 NAPAP (National Acid Precipitation Assessment Program) Report to Congress
- EPA 1993 Report to Congress on Effects of 1990 CAAA on Visibility in Class I Areas

Section III provides a summary of published research papers relevant to visibility research (full citations are included in a Reference section at the end of the document). Appendix D identifies major scientific conferences involving visibility research not cited elsewhere in this document. Many of these conferences did not publish formal proceedings, and individual presenters may or may not have published the research.

Section IV contains a summary of the visibility related research currently being performed by:

- Grand Canyon Visibility Transport Commission (GCVTC)
- Environmental Protection Agency (EPA)
- National Park Service (NPS)
- Department of Energy (DOE)
- Electric Power Research Institute (EPRI)
- National Oceanic and Atmospheric Administration (NOAA)

Some of this research is conducted in support of programs such as global climate change, but has implications for visibility research.

Section V discusses visibility research in the planning stages.

II. Synopsis of Prior Reports

There have been four significant reports issued since the passage of the CAAA in 1990. The contents of these reports are summarized below in chronological order.

In addition to these major reports, conferences addressing visibility research results were also critical in the transfer and coordination of visibility research. The primary purpose of

each of these conferences was to provide a forum for discussion on active visibility related research. The conference presentations are not summarized in this document. However, dates, sponsors, and references are provided in Appendix D.

II.A. National Research Council (NRC), National Academy of Sciences Report

The National Research Council report, *Protecting Visibility in National Parks and Wilderness Areas*, was issued January 1993, outlined working principles for assessing the relative importance of anthropogenic emission sources that contribute to haze in Class I areas and for considering various alternative source control measures. Because of the importance of this document, the Executive Summary is quoted in major part.

Executive Summary

Many visitors to America's national parks and wilderness areas are unable to enjoy some of the beautiful and dramatic views that would prevail in the absence of air pollution. Scenic vistas in most U.S. parklands are often diminished by haze that reduces contrast, washes out colors, and renders distant landscape features indistinct or invisible.[1] The National Park Service (NPS) has reported that visibility impairment caused by air pollution occurs in varying degrees at many park monitoring stations virtually all the time. Today, the average visual range in most of the western United States, including national parks and wilderness areas, is 100-150 km (about 60-100 miles), or about one-half to two-thirds of the natural visual range that would exist in the absence of air pollution.[2] In most of the East, including parklands, the average visual range is less than 30 km (about 20 miles), or about one-fifth of the natural visual range.[3]

Visibility degradation in parklands is a consequence of broader regional-scale visibility impairment. The causes of this impairment are well understood. Most impairment is caused by fine particles that absorb or scatter light. Some of these particles (primary particles) are emitted directly to the atmosphere; others (secondary particles) are formed in the atmosphere from gaseous precursors. Visibility-reducing particles and their precursors can remain in the atmosphere for several days and can be carried tens, hundreds, or thousands of kilometers downwind from their sources to remote locations, such as national parks and wilderness areas. During transport, the emissions from many sources mix together to form a uniform, widespread haze known as regional haze.

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[1]Haze degrades visibility primarily through the scattering or absorption of light by fine atmospheric particles. Visibility is the degree to which the atmosphere is transparent to visible light.

[2]Visual range is defined as the greatest distance at which a large black object can be discerned against the horizon sky.

[3]The natural visual range in the East is less than that in the arid West.

Most visibility impairment is caused by five particulate substances (and associated particulate water): sulfates, organic matter, elemental carbon (soot), nitrates, and soil dust. The major cause of reduced visibility in the East is sulfate particles, formed principally from sulfur dioxide (SO_2) emitted by coal combustion in electric utility boilers. In the West, the other four particle types play a relatively greater role than in the East. The causes and severity of visibility impairment vary over time and from one place to another, depending on meteorological conditions, sunlight, and the size and proximity of emission sources.

Congress in 1977 established a national goal of correcting and preventing pollution-related visibility impairment affecting large national parks and wilderness areas, termed "mandatory Class I areas."[4] However, the federal government and the states have been extremely slow in developing an effective visibility protection program. The present program lacks sufficient resources, and it targets few of the major types of sources of visibility impairment in Class I areas. As a result, little progress has been made toward the national visibility goal established by Congress 15 years ago.

The Clean Air Act includes two emissions control programs specifically concerned with visibility in national parks and wilderness areas. One of these, the Prevention of Significant Deterioration (PSD) program, is directed mainly at new sources; the other, a visibility protection program, largely is aimed at existing sources.

The PSD program requires that each new or expanded "major emitting facility" locating in a "clean air area" install the "best available control technology", and it establishes increments (allowable increases) that limit the cumulative increases in pollution levels in clean air areas. Many large national parks and wilderness areas are designated as Class I areas and therefore are subject to the most stringent increments. The PSD program has protected visibility to some extent by reducing the growth of emissions of pollutants that contribute to regional haze. The program's requirement that major new sources locating in clean air areas install the best available control technology has been particularly important.

But the limits on growth in air pollutant concentrations established by the PSD program have been only partially effective. First, the restrictive Class I increments apply only to large parks created before enactment of the Clean Air Act Amendments of 1977; many other scenic areas receive no special protection. Second, it is not even clear that the Class I increments ensure effective protection against new sources that might cause visibility impairment. The increments do not distinguish between particles in the 0.1-1.0 μm range—which have the greatest potential to degrade visibility—and larger particles. Moreover, increments focus on the concentration of pollution at a given time and place; but visibility impairment depends on the total magnitude of fine particulate matter between an object and an observer.

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[4]These are national wilderness areas and national memorial parks larger than 5,000 acres, national parks over 6,000 acres, and international parks. Any such area must have been in existence on August 7, 1977, the date the Clean Air Act Amendments of 1977 were signed into law, to be considered a mandatory Class I area.

A 1990 report by the U.S. General Accounting Office (GAO) discussed other flaws in the PSD program. The GAO found that federal land managers had not fully met their responsibilities to review PSD permit applications, due to lack of time, staff, and data and also due to the failure of the U.S. Environmental Protection Agency (EPA) to forward permit applications. Moreover, many sources of visibility impairment in national parks and wilderness areas are exempt from PSD requirements, because they are considered minor sources, or because they existed before the PSD program took effect in the 1970s.

The other visibility protection program under the Clean Air Act requires states to establish measures to achieve "reasonable progress" towards the national visibility goal and to require the installation of the "best available retrofit technology" on large sources contributing to visibility impairment in mandatory Class I areas. In 1980, EPA issued rules aimed primarily at controlling "plume blight" (impairment due to visible plumes from nearby individual sources). At that time, EPA also expressed its intention to regulate regional haze at some future date "when improvement in monitoring techniques provides more data on source-specific levels of visibility impairment, regional-scale models become more refined, and scientific knowledge about the relationships between air pollutants and visibility impairment improves." More than a decade later, despite major advances in monitoring techniques, regional-scale models, and scientific knowledge of visibility impairment, EPA has yet to issue rules for regulating regional haze. Instead, EPA's rules require only the regulation of impairment that is attributable to individual sources through the use of simple techniques. This has greatly weakened the visibility program's effectiveness. Fourteen years passed until the first pollution source was required to control its emissions under this program.

Emission-control measures already adopted or planned will not solve the nation's visibility problems. The acid rain control program established by the 1990 Clean Air Act Amendments has been predicted to reduce SO_2 emissions in the East by about 36% by 2010. That reduction probably will improve visibility in much of the East but will eliminate only a fraction of the anthropogenic visibility impairment. In the West, where most Class I areas are located, projections done for EPA indicate that the acid rain control program will halve, but not entirely prevent, expected growth in SO_2 emissions between now and 2010.

THE CHARGE TO THE COMMITTEE

This report was prepared by the NRC's Committee on Haze in National Parks and Wilderness Areas. The committee was convened by the Council's Board on Environmental Studies and Toxicology in collaboration with the Board on Atmospheric Sciences and Climate of the Commission on Geosciences, Environment, and Resources. The committee's members have expertise in meteorology, atmospheric chemistry, air-pollution monitoring and modeling, statistics, control technology, and environmental law and public policy. The committee's work was sponsored by the U.S. Department of the Interior (National Park Service, Bureau of Reclamation, and Office of Environmental Quality), U.S. Department of Energy, U.S. Environmental Protection Agency, U.S. Department of Agriculture (Forest Service), the Arizona Salt River Project, and Chevron Corporation.

The committee was charged to develop working principles for assessing the

relative importance of anthropogenic emission sources that contribute to haze in Class I areas and for considering various alternative source control measures. It also was charged to recommend strategies for filling critical scientific and technical gaps in the information and data bases on (1) methods for determining individual source contributions, (2) regional and seasonal factors that affect haze, (3) strategies for improving air-quality models, (4) the interactive role of photochemical oxidants, and (5) scientific and technological considerations in choosing emission control measures.

In 1990, the committee published an interim report, Haze in the Grand Canyon, which evaluated the National Park Service's Winter Haze Intensive Tracer Experiment (WHITEX) report on the causes of wintertime haze in the region between the Grand Canyon and Canyonlands National Park. The WHITEX report by NPS had asserted that the Navajo Generating Station (NGS), a large coal-fired power plant in Page, Arizona, is a principal contributor to visibility impairment in Grand Canyon National Park (GCNP). Our committee's interim report concluded that, at some times during the study period, NGS contributed significantly to haze in GCNP, but that WHITEX failed to quantitatively determine the fraction of sulfate particles and resulting haze attributable to NGS emissions. The committee identified flaws in the models used to estimate NGS's contribution, in the interpretation of those models, and in the data base. The committee found that sources other than NGS appeared to account for a significant fraction of haze observed in GCNP during the study period. Thus, if NGS emissions were to be controlled, visibility impairment in GCNP would be reduced but not eliminated.

THE COMMITTEE'S APPROACH TO ITS CHARGE

In this final report, the committee examines patterns of visibility degradation and haze-forming pollutant concentrations in various parts of the United States resulting from natural and anthropogenic sources of gases and particles. . . . It considers the regulatory and institutional frameworks for efforts to improve and protect visibility, including the Clean Air Act. . . . This report also reviews the scientific understanding of haze formation and visibility impairment, including the meteorological and chemical processes responsible for the transport and transformation of gases and particles in the atmosphere, as well as chemical and physical measurement techniques. . . . The approach of first relating source emissions to aerosol composition, and then relating aerosol composition to visibility, is fundamental to most of the committee's analyses.

In evaluating methods for source identification and apportionment, this report considers the technical adequacy (including degree of uncertainty), flexibility, and difficulty of implementation of the various approaches. . . . In discussing control techniques, the report describes the emissions reduction potential of various control measures and illustrates the translation of control measures into a rough prediction of effects on visibility. . . . The report also considers policy implications of scientific knowledge about visibility and recommends approaches to remedy scientific and technical gaps that limit present understanding of source effects on visibility and the ability to evaluate control measures. . . .

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The complete design of a program for protecting and improving visibility in

Class I areas must involve many policy issues outside the bounds of science and the committee's expertise. However, present scientific knowledge about visibility impairment in Class I areas has several important implications for policy makers.

> Progress toward the national goal of remedying and preventing man-made visibility impairment in Class I areas (Clean Air Act, Section 169A(a)) will require regional programs that operate over large geographic areas and limit emissions of pollutants that can cause regional haze.

Most visibility impairment in national parks and wilderness areas (Class I areas) results from the transport by winds of emissions and secondary airborne particles over great distances (typically hundreds of miles). Consequently, visibility impairment is usually a regional problem, not a local one. Regional haze is caused by the combined effects of emissions from many sources distributed over a large area, rather than of individual plumes caused by a few sources at specific sites. As a result, a strategy that relies only on influencing the location of new sources, although perhaps useful in some situations, would not be effective in general. And of course, such a strategy would not remedy the visibility impairment caused by existing sources until those sources are replaced.

> A program that focuses solely on determining the contribution or individual emission sources to visibility impairment is doomed to failure. Instead, strategies should be adopted that consider many sources simultaneously on a regional basis, although assessment of the effect of individual sources will remain important in some situations.

Because haze is caused by the combined effects of the emissions of many sources, it would be an extremely time-consuming and expensive undertaking to try to determine, one source at a time, the percent contribution of each source to haze. For instance, the efforts to trace the contribution of the Navajo Generating Station to haze in the Grand Canyon National Park took several years and cost millions of dollars without leading to quantitatively definitive answers. Moreover, there are (and will probably continue to be) considerable uncertainties in ascertaining a precise relationship between individual sources and the spatial pattern of regional haze.

Assessment of the contribution of individual sources to haze will remain useful in some situations. For instance, a regional emissions management approach to haze could be combined with a strategy to assess whether locating a new source at a particular location would have especially deleterious effects on visibility. . . . the committee has set out working principles for attributing visibility impairment to individual sources.

> **Visibility impairment can be attributed to emission sources on a regional scale through the use of several kinds of models. In general, the best approach for evaluating emission sources is a nested progression from simpler and more direct models to more complex and detailed methods. The simpler models are available today and could be used as the basis for designing regional visibility programs; the more complex models could be used to refine those programs over time.**

After identifying which pollutants are impairing visibility for a given region, it is useful to apportion visibility impairment among contributing sources to the extent possible so that the relative effectiveness of alternative control measures can be evaluated. Source apportionment models of varying degrees of accuracy and complexity can be used to analyze regional haze problems, although no single source-apportionment method is necessarily best for all visibility problems. Simpler methods are most effective in the early stages of source apportionment, with the more complex methods being applied, if necessary, to resolve difficult technical issues.

For regional haze problems, the committee recommends use of the following models, in order of increasing sophistication:

- *Speciated rollback models*. These are simple, spatially averaged models that assume changes in pollutant concentrations to be directly proportional to changes in regional emissions of these pollutants or their precursors.

- *Hybrid combinations of chemical mass balance receptor models a different source-oriented secondary particulate mass formation model, and used with empirical data for pollutant scattering and absorption efficiencies*. Receptor models are models that infer source contributions by characterizing atmospheric aerosol samples, often using chemical elements or compounds in those samples to identify emissions from particular source types. Hybrid models are formed by combining two or more separate modeling techniques.

- *Hybrid combinations of mechanistic models for transport and secondary particulate mass formation with measured particle size-distribution data to facilitate light scattering calculations*. Mechanistic models are 3-dimensional, computer-based models that simulate the atmospheric transport, dispersion, chemical conversion, and deposition of pollutants as faithfully as possible.

Speciated rollback models are available now; . . . the committee uses such a model to illustrate apportionment of regional haze. The recommended hybrid combinations could be assembled from available components.

To assess the contribution of an existing single source to visibility impairment, photographic and other source identification methods could be used in simple cases. More complex situations require the use of hybrid combinations of chemical mass-balance or tracer techniques with secondary particle models that include explicit transport calculations and an adequate treatment of background pollutants. For complex applications that require the greatest sophistication, the most advanced reactive plume models available should be used with measured data on particle properties in such plumes and should be accompanied by an adequate treatment of background pollutants.

To assess new single sources, the most advanced reactive plume models available should be used with measured data on particle properties in the plumes of similar sources and accompanied by an adequate treatment of background pollutants.

To analyze a single source at the regional scale, a description of the source in question should be inserted into an appropriately chosen multiple-source description of the regional haze problem.

The next step in designing a visibility protection strategy is to determine whether methods for controlling visibility-impairing emissions exist or can be developed and to assess the effects of alternative sets of controls. The committee's analysis of one control scenario indicates that application of commercially available emission controls would reduce but not eliminate anthropogenic visibility impairment; the greatest improvement would be in the East. (This analysis should not be construed as endorsing a technology-based or any other specific control strategy.)

Visibility policy and control strategies might need to be different in the West than in the East.

Haze in the East and in the West differ in important ways. Haze in the East is six times more intense than in the West because of the much higher levels of pollution in the East. Were all anthropogenic pollution to disappear, visibility would still be greater (by about 50 percent) in the West. In relatively clean areas, small increases in pollutant concentrations can markedly degrade visibility; increases of the same magnitude are less noticeable in more polluted areas. Hence, visibility in Class I areas in the West is particularly vulnerable to increased levels of pollution. Moreover, the West contains most of the nation's large national parks and wilderness areas, which can be fully appreciated only when visibility is excellent. The East, however, contains a large population to enjoy the benefits of any improvement in visibility in that region.

In the East, sulfates derived from SO_2, emissions from coal-fired power plants account for about one-half of all anthropogenic light extinction. Reductions in these emissions are expected to occur in the next two decades as a result of the 1990 Clean Air Act Amendments' acid rain control program. In the West, no single source category dominates; therefore, an effective control strategy would have to cover many source types, such as electric utilities, gasoline- and diesel-fueled vehicles, petroleum and chemical industrial sources, forest-management burning, and fugitive dust.

Efforts to improve visibility in Class I areas also would benefit visibility outside these areas.

Because most visibility impairment is regional in scale, the same haze that degrades visibility within or looking out from a national park also degrades visibility outside it. Class I areas cannot be regarded as potential islands of clean air in a polluted sea.

Reducing emissions for visibility improvement could help alleviate other air-quality problems, just as other types or air-quality improvements could help visibility.

The substances that contribute to regional haze also contribute to a variety of other undesirable effects on human health and the environment. For example, SO_2 is a precursor of sulfuric acid in acid rain, oxides of nitrogen (NO_x) and volatile organic compounds (VOCs) are precursors of lower-atmosphere ozone, and fine atmospheric particles are a respiratory hazard. Such particles can influence climate by interacting with incoming solar radiation and by modifying cloud formation. Policy makers should consider the linkages between visibility and other air-quality problems when designing and assessing control strategies.

Achieving the national visibility goal will require a substantial, long-term program.

The national visibility goal is unlikely to be achieved in a short time. Policy makers might develop a comprehensive national visibility improvement strategy as the basis for further regulatory action, and establish milestones against which progress toward the visibility goal could be measured.

> **Current scientific knowledge is adequate and control technologies are available for taking regulatory action to improve and protect visibility. However, continued national progress toward this goal will require a greater commitment toward atmospheric research, monitoring, and emissions control research and development.**

The slowness of progress to date is due largely to a lack of commitment to an adequate government effort to protect and improve visibility and to sponsor the research and monitoring needed to better characterize the nature and origin of haze in various areas. The federal government has accorded the national visibility goal less priority than other clean-air objectives. Even to the extent that Congress has acted, EPA, the Department of Interior, and the Department of Agriculture have been slow to carry out their regulatory responsibilities or to seek resources for research.

RECOMMENDED RESEARCH

The committee addressed the need to alleviate scientific and technical gaps in the areas of visibility and aerosol monitoring and measurement, source apportionment, and emissions control technology. The committee considered what measures might be taken to understand better the sources of haze, possible means of reducing emissions from those sources, and alternative ways of preventing future visibility impairment in Class I areas.

The committee emphasizes that the need for additional research does not imply that further regulatory action, if otherwise warranted, to improve visibility in Class I areas would be premature. The authority of regulatory agencies to act without complete scientific knowledge is clearly implied in the Clean Air Act. Moreover, visibility impairment is probably better understood and more easily measured than any other air-pollution effect. The remaining gaps in knowledge of visibility are primarily a symptom of the lack of a strong national commitment to enforcing the visibility protection provisions of the Clean Air Act.

Resources for research are limited; therefore, precautions should be taken to ensure that the visibility protection activities of the federal land management agencies, EPA, the Department of Energy, and state and local air agencies are of the highest possible quality. In addition, a greater effort is needed for formal publication of scientific work in independent, peer-reviewed literature.

The committee recommends establishing an independent science advisory panel with EPA sponsorship to help guide the research elements of the national visibility program. This panel could address the need for wider participation by the scientific community in addressing visibility problems.

EPA should build upon and expand its efforts to track the success of the PSD program. In particular, information is needed about the potential of new sources to reduce visibility in Class I areas and about the effects on such areas of the new emissions trading programs of the 1990 Clean Air Act Amendments. EPA's current visibility-screening model needs to be revised to consider the contribution of an individual source to regional haze.

Research on relating human judgments of visibility to objective measures, such as light extinction, should continue. The results should be used to inform decision makers and the public about the perceptibility of predicted visibility changes.

Areas in which research is needed include atmospheric transport and transformations of visibility-impairing pollutants, the development of models that can better apportion haze among sources, and improved instrumentation for routine monitoring and for obtaining data that can be used to evaluate models. Monitoring and research must be closely coordinated. Better models, however, are not enough. Any model, even the simplest or most refined, depends on good empirical data on the airborne particles that cause haze and on their sources. Greater resources are needed to develop these data.

Monitoring Strategies

If national visibility monitoring networks are to achieve their goals, a long-term commitment to establishing and financially supporting these networks is essential. Monitoring programs should be able to relate visibility impairment to its sources on a scale commensurate with regional haze events and the distribution of major emissions sources. Monitoring networks in the East need to be expanded to track visibility improvements associated with reductions in SO_2 emissions. Wind observations should be evaluated to ensure that atmospheric transport is represented accurately.

A consensus should be developed on the specific instrumentation to be used for monitoring light extinction. Standards should be established for the performance characteristics of the instrumentation. Future measurement programs should devote increased attention to quality assurance and control. Strengthening the quality assurance and control program of the Interagency Monitoring of Protected Visual Environments (IMPROVE) network should be a high priority.

Greater attention should be given to the implications that planned changes in airport visibility monitoring hold for research on visibility impairment. Airports should be equipped with integrating nephelometers sensitive enough to measure the range of haze levels encountered in the atmosphere.

Measurement Methods

Current measurement methods permit reasonable estimates of the average contributions of major aerosol constituents to atmospheric visibility impairment. However, several aerosol measurement methods need to be developed or improved for the following:

- Accurate measurement of organic and elemental carbon particles, especially at low concentrations
- Routine measurement of the water content of airborne particles

- Measuring particle size distributions
- Continuous measurement of sulfates, organics, elemental carbon, nitrates, and elemental composition
- Solar- and battery-powered measurement for use in remote areas.

The committee recommends using high-sensitivity integrating nephelometry for routine visibility monitoring. This technique, which measures the scattering of light from an air sample drawn through an enclosed cell, can provide accurate data at reasonable cost. Nephelometer data can be compared with measured particle concentrations at the same point to determine the contributions of different pollutants to visibility impairment. A readily available, easily serviced, and electronically up-to-date instrument with adequate sensitivity for good and poor visibility is needed. Nephelometer measurements of light scattering should be supplemented with independent measurements of light absorption. Instrumentation for continuous measurements of particle absorption coefficients should be developed.

Source-Apportionment Modeling

Source-apportionment models require better input data on source emissions, along with unified procedures for testing individual sources. Emissions data need to be integrated more accurately into overall emissions inventories. The inventories requiring the most improvement are those for primary organic and elemental carbon particles and gaseous VOCs.

Models should be validated using existing data sets from comprehensive field studies. Mechanistic models and hybrid receptor models should be included in validation studies.

Receptor models require substantial source testing and ambient emissions measurements to improve emissions profiles for sources of haze. Standard protocols for the release and sampling of tracers should be developed, along with field studies to verify these protocols. Inexpensive and relatively short-lived tracers are needed to distinguish the emissions of similar sources.

Research should also continue toward the development of advanced mechanistic models. Two kinds of mechanistic models are especially needed: (1) an advanced reactive model for analysis of visibility-impairing plumes from single sources; and (2) a grid-based, multiple-source regional model for analysis of regional haze problems. The development of such models will require significant refinement in the understanding of processes that affect particle size distributions. Critical processes include atmospheric emissions of particles and gases that play a role in the production of secondary particles, and gas-to-particle conversion. Measurement programs that are intended to acquire such information should be designed in collaboration with modelers to ensure that the results are suitable for model development and validation. . . .

FUTURE DIRECTIONS FOR PROTECTING AND IMPROVING VISIBILITY

Present scientific knowledge has important implications for the design of programs to protect and improve visibility. What is needed, overall, is the recognition that any effective visibility protection program must be aimed at preventing and reducing regional haze. An effective program must, therefore,

control a broad array of sources over a large geographic area. Such a program would mark a considerable break from the present approach of focusing on visible plumes from nearby sources and of attempting to determine the effects of individual sources on visibility impairment.

While visibility impairment is as well understood as any other air pollution effect, gaps in knowledge remain. Filling these gaps will require an increased national commitment to visibility protection research. We believe that the time has come for Congress, EPA, and the states to decide whether to make that commitment.

II.B. IMPROVE 1993 REPORT

The Interagency Monitoring of Protected Visual Environments (IMPROVE) network provides an important link in the understanding of visibility. This network, mentioned in the monitoring discussion in the NRC Executive Summary, is intended to provide a basis for establishing a consensus on monitoring light extinction and standards for the quality of the resulting data.

The specific objectives of the IMPROVE program are:

(1) Establish current background visibility in Class I areas;

(2) Identify chemical species and emission sources responsible for existing man-made visibility impairment; and

(3) Document long-term trends.

IMPROVE Network

The IMPROVE network incorporates quality assurance and self-consistency between measurements. The NRC Committee recommended increased attention to quality assurance and control and that a consensus be developed regarding instrumentation to be used for monitoring light extinction. By measuring visibility routinely at the IMPROVE network over a period of time, the trends can be assessed. The following paragraphs present a brief description of the network and the findings in the IMPROVE 1993 Report which was issued February 1993 (Sisler, Huffman and Latimer, 1993).

Understanding light extinction is important in understanding variations in visibility. The light extinction coefficient is calculated from the measured aerosol species concentrations by multiplying the concentration of a given species by its light extinction efficiency, and summing over all species. The light extinction efficiency for sulfates and nitrates, as well as for some organics which are hygroscopic, increases with increasing

relative humidity. The extinction efficiencies used to estimate the light extinction for soluble species are adjusted for the seasonal and annual average relative humidity at each site.

The IMPROVE network consists of thirty-six protocol sites, established to characterize the distribution of visibility and aerosol concentrations over the United States. Each site has aerosol monitoring and scene monitoring (automated cameras) equipment. However, only 20 sites have optical monitoring equipment (transmissometers) to measure light extinction. Transmissometers measure the light transmitted from an artificial source through the atmosphere over a distance (one to fifteen kilometers) to a detector.

Relative humidity is measured continuously at the transmissometer sites. Simultaneous measurements are taken of elemental sulfur and sulfate ions concentrations. The aerosol monitoring includes a PM-10 sample and three PM-2.5 samples on Teflon, nylon, and quartz filters. The IMPROVE sampler is programmed to collect two 24-hour duration samples per week. The network provides for the estimation of organic mass in two different ways: hydrogen mass measured on the Teflon filter; and organic carbon mass measured on the quartz filter.

IMPROVE Findings

The physical and chemical properties of particles and aerosols in the atmosphere affect the light absorption and light scattering efficiency of the atmosphere. Among the particle and aerosol properties that are important are: size; acidity; and chemical composition.

Elemental carbon is one of the materials that absorbs light. However, an analysis of the network data suggests a ratio of light absorption coefficient to elemental carbon mass twice as large as expected. The difference between these observations and traditionally accepted values may be explained by two factors: (a) light absorption is impacted by substances other than elemental carbon; and/or (b) uncertainties in the absorption and carbon measurement methods.

Fine aerosols, (diameters less than 2.5 μm), are more efficient at light scattering than coarse aerosols. The network data in Appendix B indicate that fine aerosol concentrations are highest in Washington, D.C., in the Appalachian Mountains, and southern California. The lowest concentrations occur in the Great Basin in Nevada, the Colorado Plateau in the Four Corners states, and in Alaska.

The composition of the fine aerosol varies with the geographic location and season. Of the 19 regions in the IMPROVE network, organic carbon is the largest single component in nine

regions. Sulfate is the largest single component of fine aerosol in six regions, primarily in the East. The contributions of organic carbon and sulfate are approximately equal in three regions (Boundary Waters, Sonoran Desert, and West Texas). Nitrate is the largest component of fine aerosol in Southern California only. In general, average fine mass aerosols concentrations are highest in summer, soil concentrations are highest in spring or summer, and nitrate concentrations are generally highest in winter or spring.

The acidity of sulfate aerosol measured by the network was estimated statistically from concentrations of hydrogen, sulfate and organic carbon. Sites identified as acidic by this procedure were located in the following national parks: Volcanoes in Hawaii; Mount Rainier in the Pacific Northwest; Point Reyes, Redwoods, and Pinnacles in Northern California; Shenandoah in the East; and Tonto in southeastern Arizona.

A spatial examination of reconstructed light extinction (Appendix C) demonstrates a variability much like the spatial variability of fine aerosol concentrations (Appendix B). Contributions to the light extinction from coarse particles and fine soil, sulfate, organics, nitrate, and light absorbing carbon also are summarized in Appendix C. Since relative humidity (and hence the light scattering efficiency of sulfate, nitrate, and some organics) is higher in the East than in the West, the difference between eastern and western light extinction is even more pronounced than accounted for by the difference in aerosol concentrations. In the Appalachian Mountains, sulfate accounts for 2/3 of the total aerosol light extinction on an annual basis, and 3/4 of the total in summer. Organic carbon is the largest single contributor to light extinction in four of the 19 regions (Great Basin, Northern Rockies, Sierra Nevada, and Sierra-Humboldt). Higher extinction occurs in summer because of elevated sulfate and carbonaceous aerosol concentrations.

Direct measurements of light extinction for all periods, excluding conditions of fog, precipitation, and low clouds, show the same pattern of high light extinction (low visibility) in the Eastern U.S. and, to lesser extent, in Southern California. This agreed with the reconstructed light extinction. Measured light extinction is generally within 10% of the reconstructed values calculated from the measured concentrations of the major aerosol species. However, reconstructed extinction is about 80% of measured light extinction in the Appalachian Mountains during summer and in the Pacific Coast, Southern California, Sonoran Desert, and West Texas regions and 50% of measurement extinction at Yosemite in Sierra Nevada.

The human eye and mind are not able to detect small changes in light extinction. However, a measure of human perception, the

deciview scale[5], indicates the effect of aerosol on human visibility. Based on this index, the best visibility was indicated to be at Bridger Wilderness, but good visibility was also indicated at the Great Basin, most of the Colorado Plateau and parts of the Central Rockies. Other areas were indicated to have noticeably worse visibility, e.g. the Appalachian region. The general spatial distribution noted above for the annual average visibility, as indicated by deciview, generally holds true for each season as well. The least impairment occurs in winter, peak impairment occurs in summer.

IMPROVE Recommended Research

Recommendations for future research in the IMPROVE report include research to better understand organic carbon light absorption and to develop an adjustment to the current light absorption calculation. The assumption regarding the type of hydrocarbon used to calculate the mass fraction of hydrogen and carbon in organics needs to be studied. Light absorption calculations are based upon the light absorbing capability of elemental carbon. Studies should be performed to determine whether all light-absorbing carbon is elemental, and whether the pyrolyzed carbon on the quartz filter may absorb light when in the air. The IMPROVE report suggests that light absorption correlates equally well with organic carbon and elemental carbon, and recommends that this be studied.

The IMPROVE report recommends that the relative humidity correction applied to the sulfate, nitrate, and organic aerosols be re-evaluated. The studies of sulfate and nitrate relative humidity factors are based on ammonium sulfate. Ammonium nitrate has a different deliquescence point than ammonium sulfate and a specific correction for relative humidity effects on ammonium nitrate needs to be established. Acidic sulfates, e.g., sulfuric acid and ammonium bisulfite, also need specific corrections, because they have higher water contents and higher light scattering efficiencies than ammonium sulfate. The hygroscopicity of organics is not well understood and needs to be investigated.

At many of the IMPROVE sites the calculated light extinction, as estimated from concentrations of the major aerosol species, underestimated the measured light extinction. The general and specific causes need to be determined.

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[5]Deciview scale (Pitchford and Malm, 1994) is such that one unit change corresponds to about 10% change in extinction coefficient. This small, but perceptible, change in the index is zero for pristine atmosphere and increases as visibility is degraded.

II.C. National Acid Precipitation Assessment Program (NAPAP)

The "NAPAP 1992 Report to Congress" (Chapter 4, "Ambient Air Concentrations, Deposition, and Visibility" issued June 1993) includes key findings related to visibility research. These findings address only one aspect of the research being summarized here. The research addressed by the NAPAP Report is applicable to the assessment of current sources of visibility impairing pollution and clean air corridors. The key findings are:

- Concentrations and deposition of pollutants are generally higher in the vicinity of major point sources and in urban areas than at regionally representative sites.

- The area of influence of specific sources or particular source regions on specific receptors varies with the season and with the prevailing meteorological conditions.

- Except for areas impacted by local sources, air concentrations and deposition of pollutants are highest at high elevation (locations above 1,400m) in the Appalachians.

The fate and transport of acidic-related pollutants in the atmosphere is important in the understanding of visibility because these pollutants interfere with the transmission of light. The acidic-related pollutants form particles which absorb water vapor during long transport periods, scatter light, and contribute to regional haze. The main link between acidic deposition and visibility degradation is through sulfur dioxide emissions and the production of sulfate aerosols in the atmosphere. Sulfate aerosol is an important contributor to visibility reduction.

The information presented in Chapter 4 of the "NAPAP 1992 Report to Congress" is from the IMPROVE network, which, as described in the previous section, provides basic aerosol measurements at numerous rural locations, including selected national parks and wilderness areas in the continental United States. While the IMPROVE network provides the broadest spatial resolution of any available data, IMPROVE does not include measurements in populated areas. These data from IMPROVE are evaluated for consistency with earlier data, by comparing fine mass fractions for the important aerosol species. The average percent sulfate in fine particle mass at IMPROVE rural sites (6 in East, 27 in West) appears to be quite consistent with similar sulfate data presented in an earlier NAPAP Visibility Report for rural sites (15 in East, 20 in West). The estimated 50 percent sulfate contribution to non-Rayleigh extinction in the rural East also compares well with the earlier NAPAP *Integrated Assessment*

Report, which considered only sulfate effects on extinction at rural sites in the East.

It is difficult to make a thorough comparison with the IMPROVE nitrate data, as nitrate data in earlier reports were sparse and some measurements were biased. However, the "NAPAP 1992 Report to Congress" suggests that the IMPROVE nitrate concentrations were somewhat greater in magnitude than those presented in the earlier NAPAP Visibility Report. "NAPAP 1992 Report to Congress" states that the "discrepancy is not critical, however, because the nitrate concentrations are still small compared with sulfate concentrations and because the air quality changes from acidic deposition controls are primarily for sulfates, and not nitrates."

The report evaluates trends based upon emission reductions achieved in the past and projected for the future. The 10-percent reduction in emissions of sulfur dioxide that occurred from 1980 to 1990 should have produced about a 6% improvement in visibility. The analysis of visibility trends for 1980 to 1990 is likely to be ambiguous for this level of change. The trend should be much more obvious when the CAA acid deposition control programs have been fully implemented. The NAPAP report estimated that those programs should result in a 40% emissions decrease and there should be an associated increase of 30% in visual range between 1980 and 2010 in the rural East. The report suggests that trends analysis might be enhanced by considering trends in the concentration of sulfates in the atmosphere, because sulfate should exhibit nearly twice as much relative change as visibility.

The main thrusts of the "NAPAP 1992 Report to Congress" are in the areas of visibility source apportionment, emission control technology, and fundamental scientific issues of regional haze management. Important conclusions of this report are: adequate information exists to justify new visibility protection rules; and targeting single-point sources may not be the best approach, since a wide variety of sources can contribute to the regional haze that distorts visibility.

II.D. Effects of 1990 CAAA on Visibility in Class I Areas

An EPA Report to Congress (EPA, 1993) addressed the changes that are expected in visibility conditions in Class I areas as a result of the implementation of the provisions of the 1990 CAAA (other than the added section 169B visibility protection provisions). The report-in-hand is closely linked to the 1993 EPA Report to Congress. In the 1993 EPA report, an assessment was made using key locations and a simple emissions-driven air quality analysis to ascertain areas likely to see changes in the distribution of man-made visibility-impairment related pollutants. The report used two levels of analysis. The first

or preliminary analysis used a very simple model to determine geographic regions where visibility improvement might be possible. The preliminary analysis for the Eastern U.S. concentrated mostly on changes in sulfur dioxide emissions. For the Southwestern U.S., the mixture of pollutants is more varied and less dominated by sulfur particles. Thus the analysis incorporated changes in emissions of sulfur, nitrogen, organic and primary particulate matter. The 1993 EPA report indicated that, based on the preliminary analysis, the following regions are expected to experience perceptible changes in visibility conditions: most areas east of the Mississippi River; areas west of the Mississippi River and south of Minnesota and Wisconsin; southern California; and the central California coast.

The second level of analysis employed more advanced air quality models to analyze these two regions. Using these models, the current annual average visibility conditions, expressed in standard visual range (kilometers), were estimated along with seasonal changes. Atmospheric processes which form visibility impairing particles and the resulting levels of extinction of those particles (due to humidity) vary by season.

Using the advanced air quality models, Class I areas from Maine to Georgia are estimated to experience future improvements in regional visibility conditions. The major improvements expected for Class I areas are for those areas along the central and southern portions of the Appalachian Mountains. No areas are expected to have perceptible decreases in regional visibility. There is considerable uncertainty in the analysis and single day changes can not be estimated.

Predictions of visual air quality are most uncertain for sensitive western areas due to emissions from Mexico. Uncertainty varies by pollutant type with estimates of changes in organic particle concentrations being quite uncertain, especially those formed secondarily in the atmosphere from emissions (natural and man-made) of gaseous volatile organic compounds. "Although visibility will improve in many eastern Class I areas, based on estimates of the natural annual average visibility . . . there will still be perceptible man-made regional visibility impairment in all Class I areas nationwide," i.e. the situation is improving, but there is still a problem.

III. Published Results

The published results in this section are pertinent to the "assessment and evaluation that identifies, to the extent possible, sources and source regions of visibility impairment ... as well as source regions of clear air for class I areas" (CAA §169B(a)(2)). Visibility research is a continuing activity. The central frame of reference for the research results included in this report is that they were published after the passage of the

CAAA in November 1990. Most references included in Section III of the report are to refereed journal articles, or to conference papers with published preprints or proceedings. Brief summaries of selected documents have been grouped according to the following four research areas identified in §169B(a)(1) of the CAA: monitoring; sources of visibility impairing pollution; regional air quality models; and atmospheric chemistry/visibility physics. It is important to recognize that new science published in the refereed literature is subject to scientific review and examination. The results and conclusions are sometimes controversial. The fact that research is published does not imply that the results are accepted by the entire scientific community. Rather, the publication makes it possible for others to question and challenge results. Section III merely reports the findings claimed in the publications and does not judge the credibility of the research.

III.A. Monitoring

The topic of monitoring in this report includes instrumentation, methods, networks, and identification of visibility trends, changes and patterns. Results from national and international research are reported.

Monitoring (see Appendix C of NRC, 1993, for complete background discussion) includes both direct measures of the visible light transmitted in the atmosphere as well as monitoring the chemical composition of the atmosphere. If the chemical composition of the atmosphere is known, models can be used to estimate visibility. Atmospheric gases that should be monitored because they are important in light scattering, light absorption or in particle formation include: sulfur dioxide (SO_2), nitric oxide (NO), nitrogen dioxide (NO_2), ozone (O_3), ammonia (NH_3), hydrogen peroxide (H_2O_2) and non-methane hydrocarbons.

Monitoring of fine atmospheric particles (smaller than 2.5 μm) is important as they account for much of the reduction in visibility. Analyses of fine particles can be used to infer origin as well as quantify chemical composition. Properties of particles which are important to visibility research include: size distribution; mass and chemical size distribution; carbon (organic versus elemental); and water content.

The direct measurement of visible light transmitted through the atmosphere is an important part of optical monitoring. Other factors are important to visibility as well, including the amount and color of light emitted by the viewed object and the scattering of ambient light. The average extinction coefficient over a path for which transmittance can be calculated as the sum of scattering and absorption coefficients for gases and particles along the path. In some methods, point measurements must be extrapolated to the sight path. Sight path methods include

measurements of transmittance over a long path, radiance along a sight path, and photography. Considerable scientific research related to monitoring methods was published prior to the passage of the CAAA of 1990 and is not included here. Many of the science issues related to monitoring were identified by NRC (1993) and were covered in the executive summary included in Section II.A.

Measurement methods for aerosols are varied and the various instruments have differing capabilities and limitations. Research has indicated potential problems with some methods for measuring aerosols and John (1993) addressed instrument performance and standards for sampling of aerosols.

Sampling Problems Related to Gas/Particle Phase

Sampling and characterization of organic carbon is plagued with problems including evaporative losses and gas adsorption on substrate. This is an area of active research, including the methods for measuring organic carbon and the size of the loss. The following are research articles that addressed this problematic area. Some research indicates that particulate organic compounds are underestimated from filters because semi-volatiles are lost. The claim is that this effect is much larger than the overestimate resulting from absorption of organic vapors on a quartz filter (Eatough et al. 1993, Lewis et al. 1991). A multi-system, multi-channel, high-volume diffusion denuder sampler, which measures these as well, was used in Provo, UT and Los Angeles, CA. Results indicate that lost particles were 0.4-0.8 μm in size and included paraffinic and aromatic compounds, organic acids and esters (Tang et al. 1994).

Sampling losses are not limited to organic compounds. Zhang and McMurry examined evaporative losses during atmospheric aerosol sampling of adsorbed or absorbed species (1991) and of fine particulate nitrates (1992), using the annular denuder and the cascade impactor.

The transition between gas and particle phase was addressed by Turpin et al. (1993) who developed a new gas/particle diffusion separation sampler to provide quality measurements of semi-volatile organic compounds. Separation is possible because gases diffuse much faster than particles. The contribution from the particulate phase is the difference between the total concentration and the gas-phase concentration. Results from this sampler agreed well with theory.

An annular diffusion denuder and filter pack system sampled gaseous HNO_3, HNO_2, and SO_2 and also nitrate, nitrite and sulfate particles for 12-hour periods in Page, AZ, January 15 - February 4, 1986. Results showed 88% of total nitrate was gaseous HNO_3, 97% of total nitrite was the gaseous HNO_2 and 91% of total

sulfate was the gaseous SO_2. There was good agreement between the denuder and filter pack concentrations of the HNO_3 gas, better than the agreement for particulate nitrate (Benner et al. 1991).

Improvements have been made that relate to monitoring capability. Koutrakis et al. (1993) developed a new system for atmospheric monitoring that combines a honeycomb denuder with the filter pack. The system is less costly and allows more denuders for simultaneous collection of a greater variety of gases. The system is also more convenient for large-scale monitoring studies.

Relative Humidity Effects

The NRC (1993) also recognized the need for methods related to the routine measurement of the water contents of airborne particles. Thomas and Gebhart (1994) found that measurements and theory indicate that if the aerosols are mainly in the accumulation mode, approximately 0.1 to 1.0 μm in size, there is a fairly linear relationship between photometer response and mass concentration. However, the relationship did not hold for a case with high relative humidity.

Relative humidity effects, induced by flow in the microorifice uniform deposit impactor, on sulfuric acid drop size were studied by Fang et al. (1991). Stein et al. (1994) used the DMA-impactor technique to study the relative humidity dependent bounce and density of atmospheric particles.

Particle Characterization

Other particle characteristics are important to estimating the visibility: density, vapor pressure and number of condensation nuclei. Kelly and McMurry (1992) measured the aerosol particle density by inertial classification with a differential mobility analyzer. Stolenburg and McMurry (1991) presented an ultrafine aerosol condensation counter. Zhang et al. (1993) determined particle vapor pressures using the tandem differential mobility analyzer.

The size distribution of particles is important to visibility. For elemental carbon and polycyclic aeromatic hydrocarbons, Venkataraman et al. (1994) examined size distributions of vehicular air pollution. Sloane et al. (1991) found improved precision measuring aerosol particle size by using an optical counter and a nephelometer.

Direct Measurement of Optical Properties

The NRC (1993) recommended use of high sensitivity integrating nephelometry which measures light scattering of an

enclosed air sample. An integrating nephelometer was modified to sample on an alternating basis, first from fine particles (<2.5 μm), then from all particles. This nephelometer was collocated with a transmissometer which monitored total extinction. Results indicated that the nephelometer underestimated the scattering by coarse particles by nearly half. When this bias was eliminated, the results indicated that coarse particles were responsible for one-fourth to one-third of total particle light scattering (White et al. 1994). Results apply to spring and summer in the southwest U.S.

Liquid water in aerosol particles influences light scattering. Rogers et al. (1991) looked at the estimation of liquid water using a nephelometer. Optical detectors were examined by Dick et al. (1994) for size - dependent counting efficiencies and angular scattering patterns for spherical particles of known size and composition. Hering and McMurry (1991) looked at the calibration of optical counters.

Another direct measurement of optical properties is visibility monitoring with human observations. Airports have been the source of these observations which were taken to support aviation. The NRC (1993) recognized that the human observations of visual range were being automated by the National Weather Service (NWS). The representativeness and responsiveness of the visibility sensor, Belfort Model 6220, was addressed by Bradley and Lewis (1993). The Belfort 6220 is a blend of an electro-optical sensor that measures point visibility and an algorithm to convert a time series of measurements into an estimate of surface horizontal visibility. The estimate, representative of 2-3 miles around the sensor, is adjusted for the weather for each minute before calculating a 10-minute harmonic mean. The NRC (1993) recommended that airports be equipped with integrating nephelometers. Section IV.F of this report will address some of the ongoing research on the Belfort Model 6220.

Human perception of visibility, although a direct measurement, is subjective. Human perception is being addressed with instrumentation. Henry, Shibata and Chitwood (1994) describe a new visual colorimeter for quantifying perception of color and brightness of natural objects seen through the atmosphere. Laboratory precision of color matches is 4% and accuracy is about 5%.

Coarse particles do not remain in the atmosphere as long as fine particles and do not affect visibility as much. However, coarse particles up to 10 μm are still important. John et al. (1991) found particle bombardment can cause reentrainment, oversampling due to deagglomeration of soil; and John and Wang (1991) found the sampling effectiveness of oiled collection surface decreases with loading.

Surface properties of aerosol properties are also important. Pandis et al. (1991) presented an epiphaniometer, a new instrument for continuous monitoring of the Fuchs surface of aerosol particles. It attaches neutral radioactive lead atoms to the surface and is used to determine rapid surface changes in the aerosol.

Trends

Monitoring research includes analyses related to one of the main purposes in monitoring, identifying trends or spatial patterns. There have been several papers published which examined the trend of visibility or of aerosols which are the major factor influencing visibility.

The trend in visibility in the U.S. has been examined based on human observations on visible range at airports. In the East, there were areas of improved visibility in the summer from the 1978 - 1982 to the 1988 - 1992 period, based on the 75th percentile (Figure 1, from Husar, Elkins and Wilson, 1994). In the northeast U.S., extinction coefficients calculated from the visible range show a direct relationship with the sulfur emissions in both January and July based on data from 1948 to 1983 (Husar and Wilson, 1993).

Visibility concerns extend beyond political borders. In Canada, airport visibility had not previously been analyzed because the limits placed on visibility observations were below the range needed to determine visual impairment from anthropogenic pollution. Stuart and Hoff (1994) reported a technique to remove or mitigate the bias. They claimed that this method may be used to adjust for the limits and to examine trends.

A decreasing trend (1.6-1.8% per year) of optically active tropospheric aerosol was observed by Hofmann (1993) using balloon measurements (1971-1990) over Laramie, WY. Hofmann suggests this may be related to SO_2 emission reductions in U.S. during this time. Pennick et al. (1993) using sites in New Mexico also found that aerosol loadings decreased slightly from mid 1970's to 1990 although elemental black carbon concentrations were unchanged. Organic aerosols are very important. Using gas chromatography, Hildemann et al. (1994) examined seasonal trends in ambient organic aerosol in Los Angeles and found strong peaks in the fall and winter.

Temporal patterns are also identified with monitoring data. Husar and Poirot (1992) found that particles less than 10 μm had different weekly patterns in different parts of the U.S. For example, El Paso, Texas had lower weekend concentrations. In California, Mondays are highest in San Bernadino while in Yosemite National Park and Oceanside, south of Los Angeles,

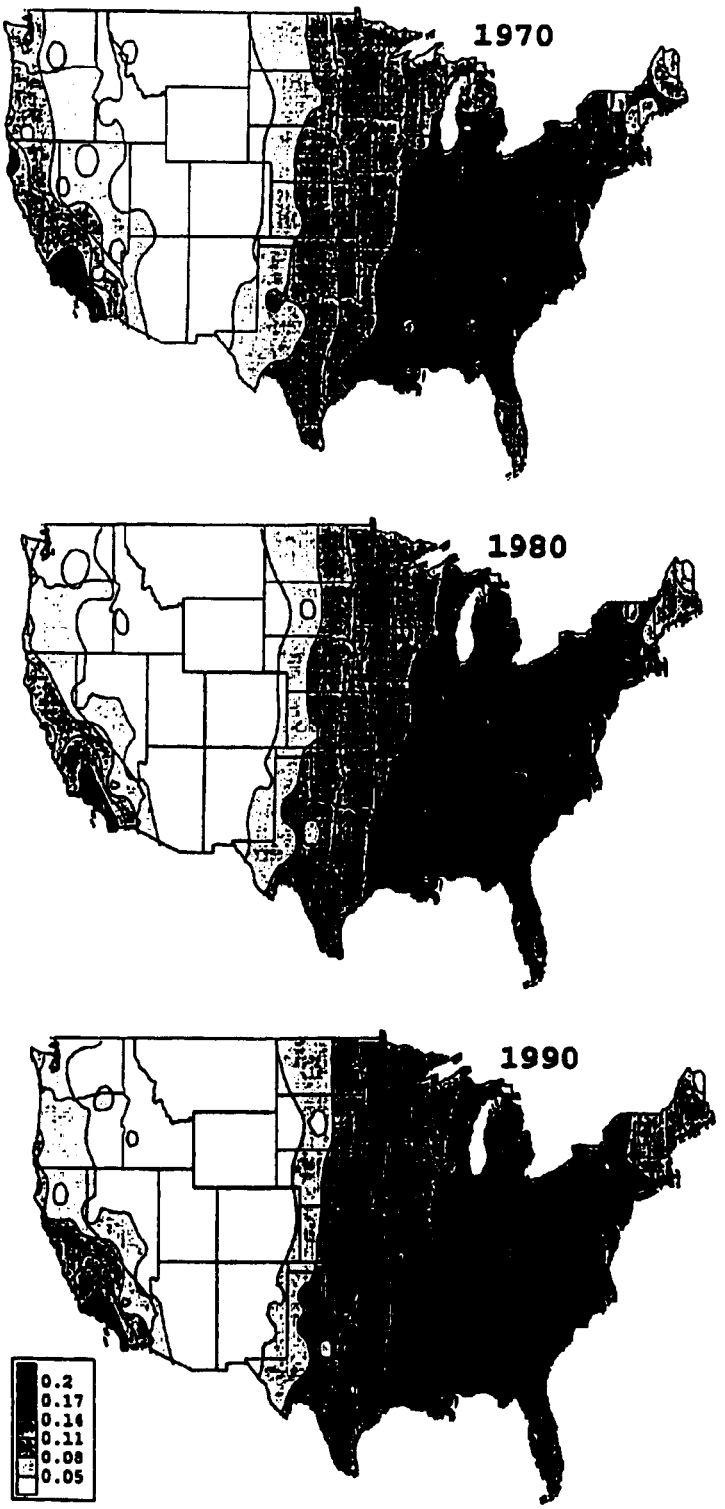

Figure 1. 75th Percentile of July-September Daily Extinction Coefficient. (Five-year average is centered on year shown). Source: Husar, Elkins and Wilson, 1994.

highest concentrations are on Sunday. These coarse particles do not affect visibility as much as fine particles so similar patterns may or may not be observed in visibility.

Eldred and Cahill (1994) examined data from 12 monitoring sites in remote Class I visibility areas from June 1982 through August 1992. The sulfate concentration in the West decreased or showed no change during that period except for concentrations in winter which increased. The sulfate in the East generally increased except for winter where it decreased. Summer increases in sulfate in the Shenandoah National Park were more dramatic. Zinc in the atmosphere, primarily associated with industrial activities, was high at the eastern sites, but showed no trend.

Remote Sensing and Global Change

The NRC (1993) noted that "satellites can be useful for characterizing the large scale distribution of haze events," but use of satellite monitoring for regional haze in Class I areas is not possible at this time. The quantification of aerosols contributing to haze over terrestrial areas is difficult. Aerosol parameters may be measured more accurately over an ocean surface with no sun glint (Durkee, et al. 1991).

Visibility research and monitoring is related to research in other programs, such as global change. In research to assess direct forcing and climate impact of aerosols, Kaufman et al. (1993) took ground-based measurements of solar transmission and sky radiance for several aerosol types (smoke, sulfate, dust, maritime aerosol) around the world. This research is of limited value, the path radiance of concern for satellite observations, and for the radiative forcing in global climate, is for the total column rather than a horizontal path.

Trends and changes in visibility related measurements have been found beyond North America. Measured global and diffuse radiation measurements, used to calculate solar radiation attenuation by aerosols, showed slight increases from 1971 to 1987 in the Slovak Republic (Lukác, 1994). However, monitoring results in Chile for a 15-year record of visual range at an airport had no trend (Frier and Firinguetti, 1994). An interference light filter spectrophotometer at the center of the European-Asian continent found small increases from 1985 - 1990, followed by a sharp decrease attributed to the Pinatubo eruption (Aref'ev and Semenov, 1994).

Common problems in interpreting monitoring data exist in the U.S. and abroad. For example, the extinction coefficient varies with the composition of the air mass, with influence from humidity, and also from changes in the stability of the boundary layer. For example, the aerosol loading in Leipzig, Germany, changes depending on the use of fuel for heating. The humidity

adjusted extinction coefficient has a strong relationship with the origin of the air mass (Uhlig, Stettler and von Hoyningen-Huene, 1994). The classification of air masses is a useful tool in interpretation of monitoring data and meteorological parameters explain aerosol extinction to some extent. Nilsson (1994) modeled the relation between aerosol extinction and meteorological parameters.

Atmospheric transport can transport aerosols formed over the oceans to the atmosphere over terrestrial areas. Much of the research on these ocean aerosols is supported by the global change program, e.g. over the Pacific Basin where research aircraft (at altitudes up to 39,000 feet) sampled aerosols. Results using particle number, size, shape, and assuming the refractive index of $(HN_4)_2\ SO_4$ yielded estimates of extinction coefficients $2.03 \pm 1.20 \times 10^{-4}\ km^{-1}$ for visible wave lengths (Pueschel et al. 1994). Although this research is not directly applicable to Class I areas in the U.S., it is relevant to long-range transport into those areas.

Global change research addresses the radiative properties of the troposphere. Changes in these properties also affect visibility. Research performed by the Atmospheric Radiation Measurement (ARM) program (of the U.S. Department of Energy) contributed to the understanding of atmospheric visibility. The ARM Science Team addressed the need for more than ground based measurements. Clouds, in particular, created large errors in estimating atmospheric radiative properties (Kinne, Bergstrom and Ackerman, 1994). Clouds are also of key interest in the formation and characteristics of particles in the atmosphere.

III.B. Current Sources of Visibility Impairing Pollution and Clean Air Corridors

The NRC (1993) states that visibility in parks and wilderness areas is largely impaired by haze originating from many different sources in a region. The degree of haze varies as do the sources of pollution contributing to that haze. The conditions under which visibility is "good" need to be understood. The concept of a Clean Air Corridor refers to the atmospheric path of air that arrives at an area associated with good visibility conditions. The Clean Air Act states that the duties of visibility transport commissions include addressing the establishment of clean air corridors in which additional restrictions on increases in emissions may be appropriate to protect visibility (CAA §169B(d)(2)).

One of the most relevant papers on the topic of the source of visibility impairing pollution, White et al. (1994) contains a number of research results of interest. The research examined back-trajectories for air arriving at the Grand Canyon and classified, if possible, the source of the air. The four

quadrants, (NE, NW, SW, SE) were considered as the source zones. Back-trajectories were calculated for air parcels arriving in the Grand Canyon during the hours of 1100 and 1700 (LST). The study found that on forty percent of the days, the two back-trajectories originated in the same quadrant as they had the previous 48-hours. They also used a region specific chemical marker as a tracer to examine one source area. Methylchloroform, a regional tracer for air from the Los Angeles basin, was monitored at the mouth of the Grand Canyon along with particulate sulfate.

In this study, White et al. (1994) found patterns of high methylchloroform at the mouth of the Canyon during April through October. The back-trajectories for these days estimated the air on those days to have been in the southwest quadrant, which includes Los Angeles, during the previous two days. However, some days with air from the same quadrant had low concentrations of methylchloroform. Back-trajectories for fine sulfate particles on the south rim were not as consistent. High sulfate particle concentrations were observed on days when the back-trajectories of the air parcels spent 3/4 of the time exclusively in only one quadrant. However, no specific quadrant was determined to be the primary quadrant of concern. Each quadrant except the northwest was identified as having at least one high concentration day at the south rim. Low concentrations were found with back-trajectories from the northwest and southwest only. High relative humidity and low visual range are associated with air from the southwest, but not the northwest. Air transported from the southwest also was coincident with reduced visual range on several days from October to January.

In conclusion, White et al. (1994) state that "clean corridors" for visibility can differ from the corridors with low sulfur and other aerosol fractions. At the Grand Canyon the best visibility occurs when air is from the north, however this seldom happens during the summer tourist season when visibility is most important. They also noted that the region to the southwest of the Grand Canyon is a regular supplier of air on days which have haze.

Joseph et al. (1993) and Eatough et al. (1992) used tracers to identify sources of sulfur oxides impacting the Grand Canyon. Using ratios of various tracers and meteorological data they established source fingerprints for air originating from the northwest, west and southwest. They found the fingerprints were distinct enough to distinguish emissions from Los Angeles Basin from emissions in San Joaquin Valley. The fingerprints for air from the northwest were similar to that for the San Joaquin for one ratio, but other ratios differed. The tracers (spherical aluminosilicate, total fluoride, fine particulate selenium, arsenic and lead) were judged to be useful in identifying sources of air impacting the Grand Canyon. Presence of these tracers

would indicate the source of the emissions affecting visibility.

Tracers also play a key role in other Clean Air Corridor research. Simonet et al. (1993) examined lignin pyrolysis products as tracers of plant classes in emissions from biomass combustion. Heaton et al. (1992) looked at tracer elements found in Rhode Island precipitation.

Source Area Atmosphere Characterization

Caka et al. (1993) studied the SO_x (gaseous SO_2 plus particulate sulfate) at the Grand Canyon during the winter intensive portion of Project MOHAVE (Measurement of Haze and Visual Effects) (January 14, 1992 - February 12, 1992) for the purpose of identifying the source and the ratio of the SO_x and its components. They found highest SO_x associated with transport from close sources east of the Grand Canyon. Dilution and increased conversion to sulfate occurred as the air was transported farther west. The highest ratio of sulfate to SO_x was associated with wet atmospheric conditions. The average concentration of sulfate was comparable in air masses from the east and from the west. Lowest concentration of both SO_2 and sulfate was associated with transport from the northwest quadrant.

In order to effectively understand source regions of both clean and dirty air, with respect to visibility, it is important to understand the composition of the atmosphere in, and of air parcels coming from, the source regions. In this regard, many researchers have characterized "source area atmosphere."

Research outside the U.S. has addressed methods to help characterize sources. Different types of air masses have different aerosol optical characteristics. Identification of these in Germany allowed for separation of local and temporal effects. The aerosol optical thickness and phase function have distinct extinction properties from marine, continental and aged air masses (von Hoyningen-Huene and Wendisch, 1994). Classification, if possible for the U.S., would be an asset in identifying Clean Air Corridor characterization.

The composition of air parcels varies and Malm, Sisler, Huffman, Eldred, and Cahill (1994) examined spatial and seasonal patterns in particle concentrations and optical extinction. They used 36 sites, mostly in the western U.S., for the period March 1988 through February 1991. This monitoring included major visibility-reducing aerosols (sulfates, nitrates, organics, light absorbing carbon, wind-blown dust) as well as light scattering and extinction. The composition of fine aerosol changes across the U.S. In the East, sulfate is the greatest component. In the Pacific Northwest organics contribute more than any other type of aerosol. Nitrate comprises the largest mass fraction of fine

particles in Southern California. In the Sonoran Desert, in western Texas and around the Great Lakes the contribution of organic carbon and sulfate are about the same. When the aerosol concentrations are used to estimate the light extinction the relative humidity must be considered.

The reconstructed light extinction is greatest in the East and in Southern California (Malm et al. 1994). Since the light scattering efficiency of nitrate, sulfate and some organics is greater because of higher relative humidity and different distribution of size of particles in the East, the differences between eastern and western light extinction are even more pronounced than the differences in aerosol concentrations. This research noted that corrections for relative humidity were based on the correction for ammonium sulfate. The correction should be larger for acidic sulfates such as sulfuric acid and ammonium bisulfate which have higher light scattering efficiencies.

Carbon and the source of carbon in the atmosphere is a key issue in Class I areas. Carbonaceous aerosol particles include natural aerosols which contain little elemental carbon, with the exception of wild fire smoke aerosols. The anthropogenic particles from combustion have more elemental carbon than organic, depending on the type of the source (Hildemann et al. 1991).

Particles from natural sources also received attention in the literature. Hallock et al. (1992) looked at carbonaceous aerosol particles from common vegetation in the Grand Canyon. Mazurek et al. (1991) looked more broadly at the biological input to visibility-reducing aerosol particles in the remote arid southwestern U.S.

One method to examine the effects of visibility impairing pollution is with the air quality models. The changes produced in visibility as a result of emission change were estimated with a model. The visibility should improve as SO_2 emissions are reduced and expectations are that with the 10 million ton reduction in SO_2 emissions called for in the Clean Air Act's market-based acid deposition control program, there will be a 21% improvement in visibility, when averaged over space and time (Malm, Trijonis, Sisler, Pitchford, and Dennis, 1994). The biggest improvement should be along the Appalachians. This estimate assumes that other factors which contribute to loss of visibility remain the same. During the summer months, sulfates account for from 50 to 78% of the loss of visibility and the visible range varies from 15-18 km in the Shenandoah and Great Smokey Mountain National Park. The Acadia National park in Maine has better visibility with 50-80 km visual range. The changes due to reduced SO_2 emissions were estimated with the Regional Acid Deposition Model (Version 2.1).

is implemented) and to determine concentration trends to measure the effectiveness of the National Strategy; 2) identifying the other factors (like wind speed, wind direction and the mixing depth, source emission profiles, and the distribution of sources throughout the urban area) that must be measured in order to derive an estimate of total area source emissions from the measured ambient outdoor concentrations; 3) developing data analysis methods to allow the trend in area source emissions to be determined despite "noise" from natural variations (like those caused by year to year changes in weather) and from the trends of point sources and mobile sources; and 4) determining if ambient outdoor data indicate that all area sources of the controlled HAPs have been recognized (that is, do the ambient concentrations reconcile with EPA's understanding of the emission sources?)

Human Exposures

The key research questions for Human Exposures are:

- What are the human exposures to HAPs?
- What are the routes of exposure?

What is the distribution of human exposures to the various HAPs? By what route, and how effectively, do the HAPs reach humans?

Data are needed to define how people's activities and the concentration of the HAPs vary with time and to characterize how that variation will affect the distribution of exposures. Research is also needed to define those circumstances that will lead to high exposures and high potential risks, including research to identify the chemicals and circumstances that make indirect exposures important.

4.2 Research on Effects Assessment

As with Exposure Assessment, there is a need for more research into Effects Assessment. Two areas that need additional research are Internal Dose and Health Effects.

Internal Dose and Health Effects

Critical issues facing health effects researchers in trying to define the potential human health effects of hazardous air pollutant emissions from area sources are:

- How can the most substantial hazards from HAPs be identified?
- How can health risks be estimated reliably?

How can the most substantial hazards from HAPs be identified?

Hazard identification research is needed to develop, refine, and validate methods for identifying chemicals and agents that pose potential human hazards. Faster, more accurate, less expensive, and more reliable techniques are needed to determine cause and effect relationships between environmental pollutants and adverse health outcomes than the methods that are currently available. Batteries of test methods designed to evaluate potential hazards comprehensively also need to be validated. A comprehensive program to collect toxicity data also is needed. Efforts should include evaluation of realistic scenarios for concentrations and exposures.

Additionally, field studies that evaluate the biological effects of exposure to urban air pollution are needed. These field studies should combine short-term methods developed in the laboratory to screen for problem chemicals, mixtures, and/or sources, and longer-

reacts with gaseous nitric acid, a component of Los Angeles smog.

Kreidenweis et al. (1991) found that the effects of dimethylsulfide on marine aerosol concentrations varies by latitude. Kreidenweis et al. (1991) used a smog chamber to measure aerosols formed during photo-oxidation of dimethylsulfide and dimethyldisulfide and compared these results to predictions from a model of aerosol nucleation and growth. There was good agreement in the presence of NO_x, but maximum total number concentrations in dimethyldisulfide oxidation in the absence of NO_x were under-predicted.

Airships have been used to measure large aerosol and cloud droplet distributions over the ocean. Frick and Hoppel (1993) show an effect of processing marine boundary layer aerosol through stratus clouds. Parungo et al. (1992) examined the wet and dry deposition of atmospheric aerosols to the Pacific Ocean.

Other research is in progress, but results are not yet published, on Clean Air Corridors. This research will be discussed in Section IV.A., on Research in Progress under the Grand Canyon Visibility Transport Commission.

III.C. Adaptation of Regional Air Quality Models for Assessment of Visibility

An EPA project for developing modeling tools for assessing visibility impairment from single or multi-sources began in 1991. EPA and the Federal Land Managers[6] established an Interagency Work Group on Air Quality Modeling (IWAQM) (EPA, 1992) to address the coordination between Federal Agencies on the testing of modeling methods and to assist in the development of modeling guidance for Class I Prevention of Significant Deterioration (PSD) and Air Quality Related Values (AQRVs) impact assessments. The IWAQM was formed as a result of the 1990 Clean Air Act Amendments and overlapping Federal jurisdictions. For this reason, states sought help because there are multi-State/Regional issues and there were no specific recommendations regarding modeling pollutant impacts involving long-range transport and dispersion (50 to 250 kilometers). The technical work group was formed to pool resources and develop mutually acceptable modeling techniques.

Under this arrangement, EPA and its IWAQM partners reviewed "off-the-shelf" modeling techniques that can be employed in the interim for assessing PSD and AQRV impacts. It recommended (U.S. EPA, 1993) the MESOPUFF II model; this model mimics continuous

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[6]The term "Federal Land Manager" means, with respect to any lands in the United States, the secretary of the department with authority over such lands. See CAA §302(i).

release as a series of puffs, which allows simulation of the meandering transport characteristic of puffs over distances of 50 to several hundred kilometers. Conversion of SO_2 to sulfate and NO_x to nitrate is parameterized including the equilibrium of the HNO_3/NH_3/NH4/NO3 systems. In comparison to standard plume dispersion models (routinely employed for impacts involving short transport distances), the MESOPUFF II model provided a more realistic characterization of the fate of pollutants of particular concern for regional visibility impairment. MESOPUFF II, for instance, was able to better handle extended periods of near calm wind conditions, during which regional visibility impairment would be anticipated to be worse. The Federal Land Managers are developing a demonstration package to provide assistance in the utilization of this interim recommendation.

Concurrently, IWAQM has been fostering the development and testing of improved methods. Upon its review, IWAQM was convinced that improving the time and space resolution of the meteorological fields would yield a commensurate increase in the accuracy and confidence of any long range dispersion calculation scheme. Therefore, it undertook to investigate and develop a data base for testing this hypothesis. The IWAQM's approach was to commission the development of such a data base and upon consideration, selected the Penn State Mesoscale Model (MM4-FDDA) to generate a year's worth of meteorology data for the investigation. This system applies four dimension data assimilation of the NWS upper air and surface data through the Newtonian nudging technique to generate accurate and high spatial and temporal meteorological fields for the United States (Ching and Irwin, 1993).

A data base was generated at 80 km resolution on an hourly basis for an area including the contiguous United States, northern Mexico, and Southern Canada, as well as the eastern Pacific, western Atlantic and the Gulf of Mexico. After a review of candidate models, the Calpuff model was selected to be run against the meteorological data base. Using the CAPTEX (mesoscale tracer experiments), the results clearly indicated pronounced improvements with these data as compared to the conventional use of the twice daily sounding method. A user's guide for the CALMET meteorological model that incorporates the use of the MM4-FDDA data is in review (Scire, 1994).

The IWAQM (U.S. EPA, 1993) provides the assumptions for a Level I analysis technique for evaluating effects of long range transport and regional visibility. The Level I is a relatively simple analysis expected to provide a conservative estimate of concentrations due to long range transport. The assumptions are that all NO_x has been converted to nitrate and all SO_2 to sulfate.

Receptor modeling is another important modeling tool that has been applied to apportionment of sources of primary particulate emissions on local and regional scales. The chemical mass balance model's ability to apportion source emissions is limited to sources with dissimilar source profiles. The first order principles and implicit assumptions have been documented (Watson et al. 1991).

There are models for transport only. One such model uses a hybrid between Eulerian and Lagrangian approaches. The model calculates long-range pollutant transport and dispersion (Draxler, 1992). Adaptations of this model are in use for examining clean air corridor issues.

Mechanistic visibility models calculate, from first principles, the impact of gases and particles on atmospheric optical properties. The modeling extends acid deposition models or regional photochemical smog models, by calculating primary particulate substances as well as products of gas-to-particle conversion (Middleton and Burns, 1991).

Air quality modeling has been applied across the U.S. Middleton and Burns (1991) modeled the air quality in Denver, CO. Middleton et al. (1991, 1993) used a fine grid version of the RADM to examine sulfate levels in the eastern U.S. and also to examine the role of nitrogen oxides in oxidant production. Nitrogen oxides in air quality models was also addressed by Russell et al. (1993) who examined the dry deposition flux of nitrogen containing air pollutants.

Several modeling studies have been published for the Los Angeles area. Hildemann et al. (1993) modeled urban organic aerosols. Harley et al. (1993) modeled photochemical smog. They modeled the concentrations of volatile organic compounds using a lumped chemical mechanism. Harley et al. (1992) examined speciation of organic gas emissions and the detecting of excess unburned gasoline in the Los Angeles atmosphere. One of the big issues in modeling is the formation of secondary organics. Pandis et al. (1992) modeled this for Claremont, CA.

Aerosols can be incorporated into existing models, e.g. Engineering Aerosol Model Version 2 for the treatment of sulfur species, including size-dependent aerosol transport, dynamics, and chemistry for sulfuric acid aerosol buffered by ambient ammonia; it is based on the RADM Engineering Model (EM2) framework (McHenry et al. 1992).

There remain a number of unresolved issues with respect to models and their ability to accurately predict important characteristics. Wexler et al. (1994) examined the important processes that need to be included in modeling aerosols. New research has contributed to the direction which should be

addressed in models. For example, condensational growth significantly alters particle composition in the atmosphere since a large fraction of particulate matter has been shown to be of secondary nature (Turpin and Hutzicker, 1991; Eldering et al. 1991). Condensation and evaporation of volatile compounds occur due to super- or sub-saturation of chemical compounds in the gas phase. For some aerosol compounds (e.g., sulfuric acid), the vapor pressure is so low that evaporation is insignificant, whereas for other (e.g., water, ammonium nitrate), condensation or evaporation may occur depending on the meteorological and air quality conditions. Chemical equilibrium for water vapor seems to be a reasonable and well-accepted assumption, but both theoretical arguments and atmospheric measurement show that departure from equilibrium for the lower-concentration pollutants is a common occurrence (Wexler and Seinfeld, 1992; Wexler et al. 1994).

New particle formation by sulfuric acid-water nucleation may occur in the atmosphere for sufficiently high relative acidities and relative humidities. This requires a significant rate of production and a low rate of removal. Production of gas-phase sulfuric acid is primarily a daytime occurrence because it is formed by the oxidation of emitted SO_2 by OH radicals, which are formed during ozone photolysis in air containing water vapor. The primary loss mechanisms for sulfuric acid are condensation on pre-existing particles and deposition to the surface. Deposition is relatively small under neutral or stable conditions, but may be significant under unstable conditions or those with substantial wind shear. Loss due to condensation on pre-existing particles is significant if the particle loading is high, otherwise it removes sulfuric acid slowly. Typically, urban and suburban locations that have substantial sulfur dioxide emissions, but also lower particle mass loadings, cooler temperatures, and higher relative humidities, are more suitable for nucleation (Wexler et al. 1994).

Particle diffusivities are lower than for gases and typically result in deposition velocities for particles that are an order of magnitude or so lower than those for gases. For the largest particles, deposition is enhanced by gravitational settling, but this is not usually significant unless the particles are larger than 10 μm (Wexler et al. 1994).

Clouds contribute to both production and removal of particulate pollutants. Precipitating clouds provide an important removal mechanism for aerosols. Nonprecipitating clouds can also dramatically affect the aerosol size distribution through aqueous-phase reactions of dissolved trace-gas species in the portion of the entrained aerosol activated as cloud condensation nuclei. Cloud processing also affects the sulfate mass concentrations (Hoppel et al. 1994).

Some of these aerosol constituents are volatile, i.e., they are partitioned between the gas and aerosol phases, as with ammonium nitrate and ammonium chloride. In locations with very acidic aerosols such that volatile acids will not condense, or with insignificant ambient nitric and hydrochloric acid, the equilibrium calculation is not necessary. The Southern California Board model uses the Aerosol Inorganics Model equilibrium code (Wexler and Seinfeld, 1991).

Another modeling issue which needs to be addressed is flexible grid sizes and the nesting. There are certain problems associated with grid nesting (see, for example, Mathur et al. 1992). Adaptive gridding techniques are possible, but there is no consensus on which technique is the best, moving nests or adaptive grid refinements. The algorithms used for readjusting the grid are computationally less demanding than most other alternatives, as has been demonstrated in compressible flow simulations (Benson and McRae, 1992).

Visibility modeling can also be extended to the modeling of actual images. Eldering et al. (1993) developed an image based visibility model assuming theoretical light scattering and absorption in an atmosphere of parallel planes. These assumptions are used to determine sky color and the addition of light to the line of sight. Model calculations are then transformed for display as synthetic color photographs. These synthetic color photographs have been tested, both by visual comparison with standard photographs and by numeric comparison with radiometric measurements. The model requires: a clear day base photograph; chemical composition and size distribution of the aerosol; NO_2 concentration; relative humidity; temperature; mixing depth; and sun position. Distance between observer and objects is also required. The model has been shown to be successful in demonstrating visual impairment.

Global change research also uses models. Global models use geochemical mass balance to estimate amount of sulfate. Some models ignore the microphysical processes and use estimates of scattering properties from measurements (Charlson et al. 1991). Other models calculate optical properties from assumed size distributions (Kiehl and Briegleb, 1993). These models do not consider the relationship between sulfate and clouds.

Global climate research has a major focus on modeling. Models which include global sulfur and nitrogen species indicate that industrial emissions have a large impact on sulfate aerosol concentrations over large regions in the Northern Hemisphere, not just within the Northern Hemisphere industrialized regions. Langner et al. (1992) estimated the global fluxes of sulfur through the atmosphere. Aerosols are not modeled, but are estimated from observations.

III.D. Studies of Atmospheric Chemistry and Physics of Visibility

There are a number of chemistry and physics issues that are important with regard to visibility: methods for obtaining species optical efficiencies; relationship between aerosol size distributions and chemical conversion mechanisms; and radiative transfer.

Optical Efficiencies

The methods for obtaining species optical efficiencies include multiple linear regression (MLR) analysis and applications of Mie theory to measured size distributions. There is a strong effect on sulfate scattering efficiency from sulfate mass median diameter. Zhang et al. (1994) showed that sulfate and carbonaceous particles were the major contributors to fine (<2.5 μm) particle scattering during a three-month measurement period at Hopi Point, Grand Canyon and that their contributions were comparable. Scattering by nitrates and soil dust was typically a factor of five to ten smaller. This result emphasizes the need to examine carbon and organic compounds in developing strategies to maintain and improve visibility in class I areas. Variabilities in ambient sulfate size distributions caused substantial variations in sulfate scattering efficiencies. Sulfate scattering efficiencies depended on relative humidity as well.

Particle Size and Aerosol Formation

The well noted difference in visibility between the eastern U.S. and the western U.S. is due in part to particle size. The size distribution of dry particles changes from East to West. Average particle size is larger in the East. Because the East is humid there is more liquid phase oxidation of SO_2 which results in the formation of particles from 0.5 to 0.7 μm in diameter. Gas phase reactions in the West are predominant because the air is dryer. This produces sulfates from 0.1 to 0.3 μm in diameter. Thus there is a strong need to understand the chemistry of aerosol formation because it has direct effect on the aerosol optics and visibility. In addition, the size and shape of the aerosol particles are changed by aqueous-phase chemical reactions. This can occur many times and increases the efficiency of the light-scattering (Lelieveld and Heintzenberg, 1992).

There is still uncertainty in the growth of particles. Meng and Seinfeld (1994) found that two distinct modes can exist in the accumulation mode (0.1 - 1.0 μm diameter), the condensation mode (0.2 μm)and the droplet mode (0.7 μm). These modes in the sulfate size distribution were originally reported by John et al. (1990). The growth of condensation mode particles by accretion

of water vapor or by gas-phase or aerosol-phase sulfate production cannot explain the droplet mode. The mechanism may be activation of condensation mode particles to form fog or cloud drops followed by aqueous-phase chemistry and fog evaporation.

Clouds were found to influence the size distribution of particles. Hoppel et al. (1994) in a cloud chamber study examined the effect that non-precipitating water clouds have on the distribution of aerosol size. Measurements before and after a cloud cycle showed significant conversion of SO_2 to H_2SO_4 and a large change in aerosol size distribution with the cloud condensation nuclei growing more than smaller particles. Subsequent clouds cycles had small mass conversion rates. The final size of cloud condensation nuclei was 2% of the size of the cloud droplet and the pH was about 5. When H_2O_2 was the oxidant, or sufficient gaseous NH_3 was present for neutralization, the conversion of SO_2 in a droplet did not have this limit.

Methods have been developed to better determine size distribution of particles. Wiedensohler et al. (1993, 1994) compared methods to determine size distributions of low number concentration ultrafine aerosols.

Research into aerosol formation and growth by Wang et al. (1992) used measured aerosol size distributions to determine the rates of gas-to-particle conversion and to study the effects of additional SO_2 and/or NH_3 on aerosol formation and growth. Kim et al. (1993) evaluated the sensitivity of thermodynamic calculations of aerosol composition to the method used to estimate the activity coefficient. Pandis et al. (1993) simulated the size distribution of atmospheric secondary organic aerosols using a Lagrangian trajectory model with gas-phase chemistry, inorganic and organic aerosol thermodynamics, condensation/evaporation of aerosol species, dry deposition and emission of primary gaseous and particulate pollutants.

Pitchford and McMurry (1994) studied size-resolved aerosol growth, i.e. ratio of moist particle diameter to dry particle diameter, and chemical composition at the Grand Canyon in winter 1990, using data from the Navajo Generating Station and existing methods. For relative humidities above 75%, the moist particle distribution was bimodal indicating an external mixture of soluble and insoluble constituents. Both constituents grew in size. The larger, more hygroscopic particles, were composed of equal volumes of soluble and insoluble materials while the less hygroscopic were about 85% insoluble.

Koch and Friedlander (1991) presented a theoretical study of particle growth by coalescence and agglomeration. The dispersed system will form a condensed phase at high temperature and is characterized by high density of very small supercritical nuclei.

Shi and Seinfeld (1991) studied the mass transport limitation to the rate of reaction of gases in liquid droplets. They established inequalities for estimating mass transport for non-first-order chemical kinetics.

Friedlander, Koch and Main (1991) studied scavenging of coagulating fine aerosol by a coarse particle mode. They derived an analytical criterion to determine whether diffusion to coarse mode will suppress growth of fine mode. Friedlander and Wu (1994) found a linear rate law for the decay of excess surface area of coalescing solid particle.

Diefenback et al. (1992) simulated multi-droplet hydrodynamic interactions in liquid water. Kim and Seinfeld (1992) simulated multicomponent aerosol dynamics. Wolfenbarger and Seinfeld (1991) examined the inversion of aerosol size distribution to characterize the solutions.

Atmospheric Chemistry

The chemical composition was considered when Chan et al. (1992) compared three models of mixed electrolyte solutions. Mixed ammonium nitrate/ammonium sulfate at relative humidities from 35 to 70% were measured. Predictions of Zdanovskii-Stokes-Robinson model were most consistent with data.

Wang et al. (1992) looked at aerosol formation and growth in atmospheric organic NO_x systems. They used outdoor smog chambers to find aerosol-forming potential of C_7 and C_8 hydrocarbons with sunlight when mixed with NO_x. Rates of gas-to-particle conversion were estimated and effects of additional SO_2 and/or NH_3 found: SO_2 led to early nucleation burst and rapid growth of newly formed aerosol; NH_3 led to enhanced gas-to-particle conversion rate; and with both SO_2 and NH_3 there was sustained particle formation. Wang et al. (1992) simulated the aerosol dynamics which suggested that over 99% of the mass of condensible vapor is converted to aerosol by condensation even when a significant burst of nucleation occurs.

Flagan et al. (1991) studied the distribution of secondary atmospheric aerosols formed from hydrocarbons. The smog chamber study used electrical mobility measurements during atmospheric photo-chemical reactions.

Palen et al. (1992, 1993) used Fourier transform infrared analysis of aerosol formed in photo-oxidation of isoprene and beta-pinene. Aldehyde and ketone dominated the aerosols formed in isoprene photo-oxidation, alcohols and ketones in photooxidation of beta-pinene.

The scattering efficiency of acidic aerosols when the relative humidity is high differs from that of neutralized

ammonium sulfate. Saxena et al. (1993) studied measured acidities of airborne aerosols and compared them to estimates based on chemical equilibrium theory. Measured hydrogen ion concentrations were substantially higher than concentrations predicted from theory.

The atmospheric chemistry in clouds and fog play an important role in visibility. Faust et al. (1993) suggested that the chemistry in air quality models may be missing a significant reaction which produces hydrogen peroxide in cloud and fog drops. This is important because hydrogen peroxide is the limiting reagent in the dominant pathway for the oxidation of sulfur dioxide to sulfuric acid over eastern North America.

Both clouds and fog are of considerable interest. Mixing droplets with different pH that are individually in equilibrium (Henry's law) with atmosphere gives supersaturation with weak acids and bases (Pandis and Seinfeld, 1991, 1992). Pilinis et al. (1992) studied aerosol scavenging and processing in fogs. Kumala et al. (1993) used a one dimensional cloud model to examine activation and growth of cloud condensation nuclei. The system has $NaNO_3$ particles, condensing water and HNO_3 vapors. Simulations suggest enhanced concentrations of atmospheric nitric acid vapor affect cloud formation by increasing number of cloud droplets and decreasing mean size (compared to when water is only vapor). Ulevičius, Trakumas and Girgždys (1994) observed this in winter fog and concluded that the growth rate depends on particle diameter. They suggest that the aerosol growth is the result of condensation of low vapor pressure species formed by gas phase reactions and droplet phase reactions.

Reconstructed Visibility Estimates

Visibility in the Shenandoah National Park is not reconstructed well, scattering is too low. However, fine mass is well constructed if water with sulfates is included (Gebhart, Malm and Day, 1994). Sloane et al (1991) looked at size segregated fine particles by chemical species and the impact on visibility.

Sisler and Malm (1994) considered the effect of humidity on aerosols. They derived from 20 rural sites an empirical relationship between average relative humidity and average visibility impairment caused by soluble aerosols. Based on this relationship, visibility impairment was estimated for an additional 16 locations where aerosol was monitored, and reliable, but not concurrent, estimates of relative humidity were possible. Estimation of scattering by soluble aerosols must take into account the nonlinear relationship with relative humidity. Higher sulfate concentrations in the East which coincide with higher relative humidity explain much of the east-west visibility dichotomy in the United States. Size distribution of particles

was not considered.

Human Perception

An important issue in visibility is human perception. A recent paper proposed a method to measure human perception. Pitchford and Malm (1994) addressed the human physics of visibility, specifically human visual perception. A standard visual index was developed to characterize visibility through uniform hazes. The index is linear with respect to perceived visual changes over the entire range of human vision. The index, called deciview, is near zero for a pristine atmosphere with only Rayleigh scattering. The index increases by one unit for each 10% change in extinction coefficient. The one unit change is associated with a small but perceptible scenic change under many circumstances. This index has potential to be incorporated into computer simulations of air quality, optical properties and human perception.

Radiative Transfer and Mathematical Models

Models, other than the Regional Air Quality Models, addressed in Section III are important in visibility. Sophisticated aerosol and radiative transfer models are available on computers. These models incorporate realistic terrain, multiple scattering, non-uniform illumination, varying spatial distribution, concentration, optical properties of atmospheric constituents and relative humidity effects and display these in synthetic images representing modeled air quality and atmospheric conditions (Molenar, Malm and Johnson, 1994).

The air quality models discussed in Section III.C indicate the chemistry and transport particles models (size and concentration) that have been developed. Many scientists have Mie scattering models (Wilson and Reist, 1994; Sloane, et al. 1991; Zhang et al. 1994).

Modeling of the physics of aerosols has also included research results that are based more appropriately in mathematics, e.g. Zhang et al. (1994) simulated agglomeration of particles and their breakage using Fibonacci series. Dobbins, Mulholland and Bryner (1994) used fractals and found a power law relation between the number of primary particles in an aggregate and the radius. Kocifej (1994) found that a theoretical solution of radiation diffusion in a cloudless inhomogeneous molecular aerosol atmosphere could be used to calculate aerosol distribution, mean refraction index and the vertical aerosol concentration gradient. Wu and Friedlander (1993) found enhanced power law agglomerate growth in the free molecule regime.

The effects of smoke on visibility has been modeled. Accurate measurements of total scattering from smoke was

considered by Mulholland and Bryner (1994). They developed a radiometric model that was accurate within 5% for spherical particles ≤ 1.1μm using a transmission cell-reciprocal nephelometer. They estimated it would be good for up to three thousand primary spheres in an agglomerate.

Global Change Research in Atmospheric Chemistry

Global change research, driven by radiative forcing, produced results of interest to visibility, but of somewhat limited direct application. Visibility is largely concerned with aerosols in the layer of the atmosphere just above the earth's surface. Global change is concerned with the distribution of aerosols throughout the depth of the atmosphere. Because of the transport of aerosols to and from the boundary layer of the atmosphere, the results have implications for visibility.

Tropospheric aerosols affect radiative forcing and Charlson et al. (1992) reported that anthropogenic aerosol, especially sulfate, in the troposphere is important in the global radiative balance. The sulfate aerosol particles change the shortwave reflective properties of clouds as well as directly scattering the short-wave-length solar radiation.

The chemical composition of aerosols over the Northeastern Atlantic was classified for November - December, 1989 (O'Dowd and Smith, 1993). Anthropogenically influenced air masses had 80%, by number, sulfate particles with soot carbon and sea salt accounting for the remaining 20%. Sulfate was 65% in Arctic air masses. In clean maritime air with high wind, sulfate particles were less than 25%. The latter two air masses were acidic.

Clouds play a key role in global change and empirical relationships have been estimated between droplet concentration and aerosol number concentration below cloud base (Raga and Jonas, 1993). From the measurements of Hudson (1991) it appears that the growth of cloud condensation nuclei is more rapid for anthropogenic, than natural, cloud condensation nuclei. Models indicate that between a day and week is required to transform dimethylsulfide into cloud condensation nuclei active at .2-.3% supersaturation, based on assumed oxidation mechanism (Lin and Chameides, 1993; Raes, 1993). This mechanism is supported by observations (Hegg et al. 1991). In severely polluted air, gaseous nitric acid may enhance cloud condensation nuclei (Kulmala et al. 1993). The indirect effect of emissions on radiative forcing is expected to be larger for emissions into clean air (Twomey, 1991).

If there are no clouds, a method has been developed to estimate optical properties of the aerosols in the atmosphere. Wendisch and von Hoyningen-Huene (1994) used ground-based solar extinction and scattering to infer the optical aerosol properties

at various geographic locations. The method produced reasonable estimates of the refractive index which represents the main physical effects, humidity and non-sphericity.

IV. Research in Progress

This section of the report is arranged by organizational entity. The discussion presents visibility research information from several sources but does not set out the research plans of every single entity conducting noteworthy visibility research. The information presented was provided by the relevant organizations. EPA's presentation of the information does not imply an EPA position about its merits. The information is intended to provide a frame of reference for the reader who wishes to follow-up on the research described.

The research plans for the Environmental Protection Agency, National Park Service, Department of the Interior, and Department of Energy are presented. The plans of the Grand Canyon Visibility Transport Commission (GCVTC) are also included. The GCVTC was established by EPA under §169B of the Clean Air Act and includes the states of Arizona, California, Colorado, Nevada, New Mexico, Oregon, Utah, and Wyoming as well as the U.S. Department of Agriculture and Department of the Interior and the Environmental Protection Agency. The research plans for the Electric Power Research Institute (EPRI) are also included. EPRI provides research support for visibility.

IV.A. Grand Canyon Visibility Transport Commission (GCVTC)

The Clean Air Act (CAA) calls for the GCVTC to assess scientific and other available information pertaining to adverse impacts on visibility from potential or projected growth in emissions from sources in the transport region and to report to EPA by November 13, 1995 recommendations on what measures, if any, should be taken under the CAA to remedy adverse visibility impacts (CAA §169B(d)). The CAA identifies specific measures that must be addressed (CAA §169B(d)(2)).

The GCVTC has a technical committee composed of four technical subcommittees, plus a committee on assessment of alternatives on emission management options, and a committee to communicate with and to educate the public. The four technical subcommittees are emissions, aerosol and visibility, meteorology, and modeling. The tasks and status of these four technical subcommittees are provided here.

Emissions - A base year emissions inventory has been developed. Wildfire emissions are to be completed at the end of March 1995. There was concern that the estimates of emissions from mobile sources may be too low.

The inventory of emissions in Mexico will be developed. Mexican officials are meeting with the subcommittee. The inventories will be used for large regional models which are expected to be insensitive to small emissions. The NPS developed an inventory of these small emissions. Techniques to analyze the effects of these emissions may be needed.

Aerosol and Visibility - This subcommittee is overseeing contractor development of a summary of historic aerosol and visibility data.

This subcommittee, as well as the meteorological subcommittee is considering an operational definition of clean air. This definition may be necessary to determine the history of clean air. Both subcommittees considered a percent of best visibility days, from 10-30%, with 20% being used for the majority of the analyses. The definition of clean air does not predetermine existence or characteristics of Clean Air Corridors.

Meteorology - The Meteorology subcommittee has adapted a method to characterize clean air corridors. The differences between models and measured data will need to be reconciled. This subcommittee is evaluating the meteorological assumptions in the trajectory analysis for Mexico.

Modeling - Five modeling approaches are being used to examine the relationship between emission changes and visual air quality. Modeling will also be used to determine the impact of emission changes on clear days. A study is in progress to determine what changes in visibility will occur if emission sources are placed in areas currently supplying clear air to the Colorado Plateau.

Clean air corridor research by the meteorology subcommittee is evaluating several methods to characterize clean air corridor and explain why clean areas are clean. The years 1982-1992 are being examined using back trajectory analysis with the Atmospheric Transport and Diffusion Model (ATAD)[7] to examine meteorological effects. Back trajectory analysis on the cleanest 10, 20, and 30% of the days and as well as the 10, 20, and 30% of the haziest days will be the basis of the analysis. These days, determined from transmissometer measurements, will help understand clear air days. A report on the clean air corridor characterization is in preparation.

There is another task to examine the sensitivity of clean air corridors after they are characterized. A major component is

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[7]Heffter, J.L. Air Resources Laboratory Atmospheric Transport and Diffusion Model (ARL-ATAD). National Oceanic and Atmospheric Administration, Technical Memo, ERL-ARL-81, 1980.

meteorology. The air quality modeling directs this, but the characterization is required first. Only the model ATAD is available for the 10-year period. Other models have more spatial and temporal resolution and overlap for shorter time periods.

Several models are being evaluated that will permit assessment of management options. It is expected that VARED[8], CAPITA[9], ASTRAP[10], and statistical modeling[11] results will be completed in 1994. A workshop will be held to evaluate model performance. The RAMS[12] model for some summer days in 1992 should also be available.

Project MOHAVE is contributing significantly to the effort of the GCVTC. The EPA and Southern California Edison Company are partners in the project.

IV.B. Environmental Protection Agency (EPA)

The EPA conducts in-house research and also supports cooperative research with other federal organizations, with universities and with private concerns.

1. MOHAVE

The EPA is a partner in Project MOHAVE, a tracer study of emissions from the Mohave Power Plant, a 1580 megawatt coal-fired steam electric power plant. The study is intended to estimate impact of Mohave Power Plant on visibility at the Grand Canyon National Park and other Class I areas. The plant is 120 km southwest of the Grand Canyon National Park. A field study with two intensive study periods has been conducted and a final report is scheduled for November 1994. The air quality monitoring was performed with full IMPROVE samples at 10 sites and IMPROVE channel A (fine particles on a teflon filter) plus SO_2 at 21 sites. During non-intensive periods, sampling was done twice a week at 10 sites. The winter intensive study period was January

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[8]Utilities Group, Pacific Corp., Arizona Public Service, Arizona Electric Power, Nevada Power, Public Service Co. of Colorado, Public Service Co. of New Mexico, Salt River Project, Sierra Pacific Power, Tucson Electric Power, Los Angeles Water and Power, Southern California Edison, Tri-State Electric Generation and Transmission Association.

[9]R. Husar, Washington University.

[10]Department of Energy.

[11]From back-trajectories of models.

[12]R. A. Pielke, et al., 1992, Meteorol. Atmos. Phys. 49:69-91.

14 - February 13, 1992, and the summer intensive study period was July 12 - early September.

There are many participating sponsors and organizations involved in this project. The components of the project include emissions (inventory, source profile); tracer; modeling; aircraft measurements; meteorological monitoring; air quality monitoring; optical monitoring; data analysis; and quality assurance.

Emissions data from selected coal burning power plants were compiled. The emissions were profiled during part of each intensive period and there was continuous emission monitoring of SO_2 and NOx during the intensive studies.

Deterministic modeling of the meteorology was done for each day with several models at different resolutions. Linearized chemistry was included.

There was a continuous in-stack release of perfluorocarbon tracer during each intensive period. Receptor sampling was accomplished at 31 sites, including a 10-day pre-release background study. Additional tracers were released from Lake Powell during the winter, and from Tahachapi Pass and Imperial Valley during the summer. Aircraft measurements were taken on six days in the summer. Measurements were made of tracer, scattering, ozone, oxides of nitrogen, sulfur dioxide, temperature, relative humidity, turbulence and solar radiation.

Meteorological data included continuous vertical wind profiling, radio acoustic soundings to give vertical temperature and standard surface weather during the entire period. During the intensive study periods, additional surface and radiosonde data were taken. Air quality during the intensive periods was sampled every 12 hours at receptor sites and once a day at others. One site sampled H_2O_2 continuously during the summer. NH_4^+ and NH_3 were monitored periodically. Medium volume dichotomous samplers and annular denuders were operated at three sites. Denuder sampling for gas and particle phase organics was performed along with size resolved aerosol sampling and other micro-physics measurements. Optical monitoring was continuous with nephelometers and transmissometers at several sites. Time lapse photography was used.

2. Clean Air Status and Trends Network (CASTNET)

The CASTNET, operated by EPA, is an integrated monitoring network combining different long term monitoring projects and their data collection activities under one umbrella. The CASTNET Visibility Network (CVN) is one of the monitoring projects. Other projects include the Dry Deposition Network, and an Air Toxics Network. The data which are collected by the different networks include wet and dry deposition and their constituents,

ground based O_3, fine particle aerosol and its components, light scattering, light absorption and total extinction, along with standard meteorological measurements of wind speed, wind direction, temperature, and relative humidity.

The initial CVN design was completed in 1992 with the intent to provide spatial coverage for the purpose of national status and trends in visibility. Accomplishment of its goals requires the collaboration of other networks, such as the IMPROVE.

The implementation of CASTNET Visibility began in 1993 with nine sites being brought on-line, primarily in the East. Before any site is brought on-line or even selected, it must pass strict criteria. The criteria for CVN was developed from previous visibility networks and previous aerosol networks. These criteria were reviewed to address any differences that may have impacted criteria adopted for the visibility program and CASTNET in general. Sites established as of August 1994, are shown in Figure 2.

Aerosols are collected at all sites with an annular denuder system (ADS) using a 2.5 μm cutpoint (PM2.5). The samples are analyzed for fine particle mass, $SO_4^=$, NO_3, b_{abs}, trace elements, and organic and elemental carbon. The sampling time is 24 hours at a frequency of every sixth day. Four out of the nine sites are planned to be fully complemented visibility sites with aerosol, optical, and scene monitoring. These sites (NY, OH, LA, and Arendtsville, PA) have the NGN-2 nephelometer as the optical instrument selected to measure particle scattering and a camera with a telephoto lens will document the scene.

Statistical analyses of the network's ability to detect a trend were undertaken during the past year. The findings indicated that a 2% annual trend can be detected with 90% confidence in eight years at a visibility site collecting aerosol data every third day. When compared to every day sampling, a reduction of 67% in number of samples, sampling every third day produced only a 28% increase in the variance of the mean and a 13% increase in the standard error of the mean. The every sixth day sampling frequency will detect a 2% annual trend with 90% confidence in nine years.

3. Human Observer Comparison Study (HOCS)

The NRC in its report "Protecting Visibility In National Parks and Wilderness Areas" recommended the use of nephelometers in measuring visibility. The NRC was also very concerned about the transition from human to automated airport visibility monitoring planned by the NWS, the FAA and the DOD. The change has unfortunate implications for monitoring and analysis of haze

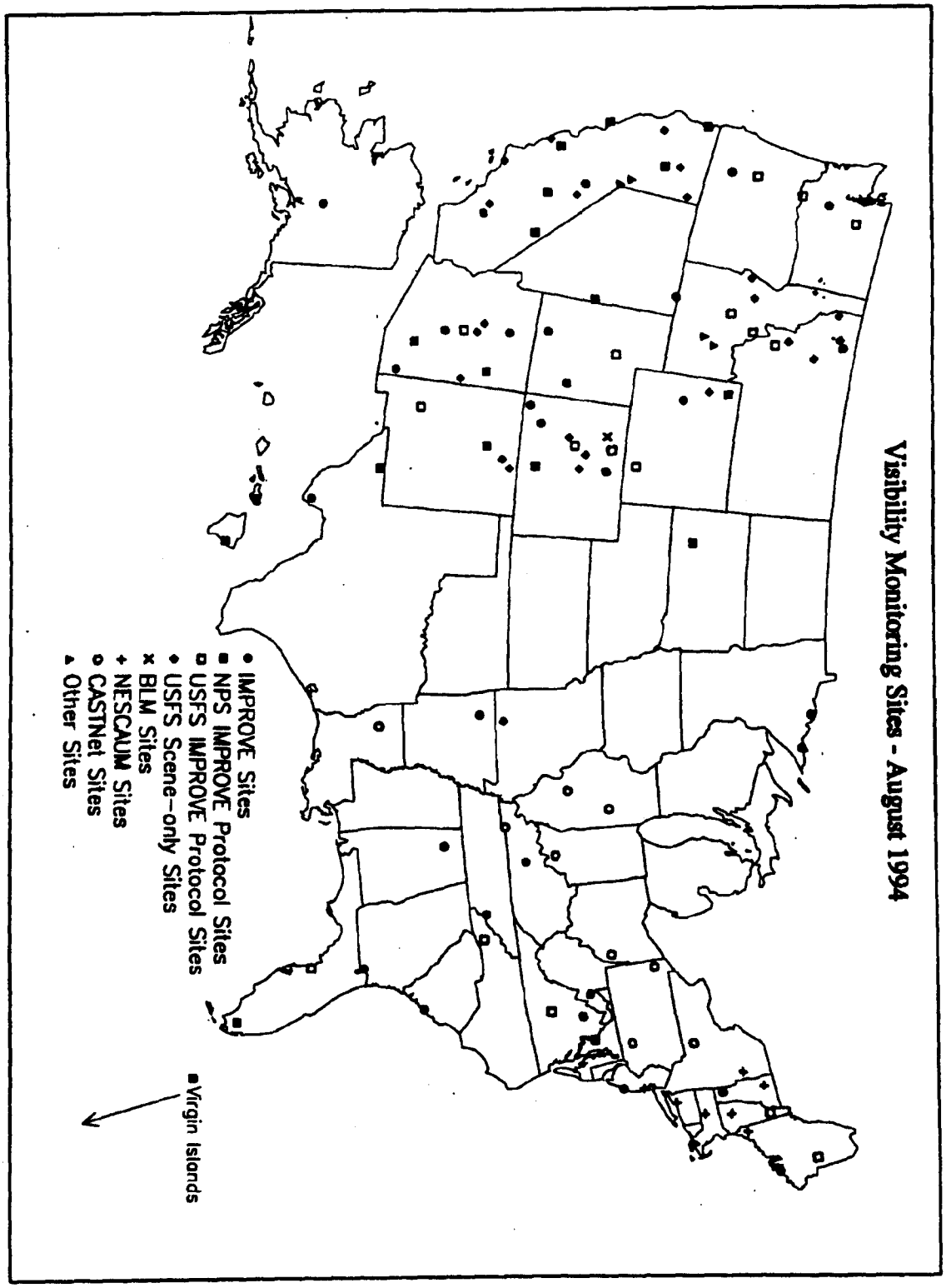

Figure 2. Visibility Monitoring Sites - August 1994. (courtesy of Air Resource Specialists, Inc., Ft. Collins, CO).

data. The Automated Surface Observing System (ASOS) will provide little or no information on the magnitude and extent of haze. In particular, this system cannot quantify haze levels corresponding to visual ranges exceeding 10 miles: prevailing range is typically much greater than this (NRC Report). Recent indications are that the Belfort instrument which is being used can provide an indication of visibility out to 35 miles. The historical record of ambient haze levels is based largely on airport visibility data from human observers. There is no other source of such information. If airport visual range measurements based on human observers cease, no information will be available for assessing long term temporal trends and spatial patterns. It is especially important that such trends be documented during the coming decade, so that the effect of the Clean Air Act's acid deposition controls on visibility can be determined.

In response to the NRC report EPA has initiated the HOCS. The purpose for the study is as follows:

* Evaluate and intercompare instrumental optical techniques used by different visibility measurement programs including NWS, IMPROVE, and the CASTNET Visibility Network. (Should include five years of SCENES[13] data).

* Establish relationships between the human observations and the NWS replacement instrumentation and EPA's visibility programs to link the new instrumentation with the historical human observer database and encourage archiving by National Weather Service of the visibility measurement to maximum distance.

* Examine the role of relative humidity on particle scattering by controlling humidity in one of two collocated integrating nephelometers.

* Conduct a summer field study at three locations with human observations: one Class I area, one rural suburban site, and one urban site.

The HOCS comparisons between nephelometers, human observations and the new ASOS visibility sensor, as well as addressing the effect of relative humidity by using nephelometers capable of controlling humidity, are to be accomplished during a summer field study at three site locations. Two sites are near airports with both human observation and the ASOS, and one site is in a Class I area with human observation data. The Class I area site will have the different nephelometers and the ASOS

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[13]Publications and presentations by participants have been documented in a 1993 EPRI report, RP1630 by C.E. McDade.

visibility sensor.

The final reports from the study are expected to be available in July 1995.

4. Visibility Cooperative Research (UNC-CH)

The EPA will cooperatively, with the University of North Carolina - Chapel Hill (UNC-CH), use existing data sets and models related to visibility and optical properties of the atmosphere to study the relationships between aerosol physical and chemical properties, meteorology, and those optical properties. There are some gaps in our knowledge of the factors influencing visibility. Models of the impact of sources on regional visibility and plumes could be improved in both accuracy and efficiency. Among the gaps are: how detailed the input parameters need to be; how much simplification is possible or desirable in models; how much time resolution is needed in field studies of visibility; and the understanding of the complex solution chemistry of the sulfate-nitrate-ammonium system.

Existing Mie codes will be used to judge the sensitivity of these complex algorithms to input parameters such as aerosol size distribution, refractive index, and concentration. Simplifications of light extinction models will be developed to reduce the need for the demanding Mie code in production models. Existing data bases will be analyzed to determine the relative importance of various species on visibility and to judge the importance of time resolution in visibility field studies. Chemical models will be used to investigate the optical impact of SO_2 oxidation in droplets and to study the ammonium nitrate replacement hypothesis. Advanced models of supersaturated solution chemistry will be introduced in the above calculations to provide more realistic treatment of liquid particles as relative humidity decreases below the deliquesence point.

5. Aerosol Equilibrium Model (In-house Research)

The EPA will develop an equilibrium model. Light scattering properties of atmospheric aerosols are affected by their chemical composition and therefore visibility models must contain modules for predicting aerosol compositions for given emission scenarios. To address this issue, efforts are underway to develop a model for predicting the gas and particle phase equilibrium concentrations of airborne inorganic pollutants. The model is based on a new method for handling the non-ideal nature of hygroscopic aerosols and will be used to predict aerosol chemical compositions for a wide range of atmospheric conditions, including cases of low relative humidities which in the past were difficult to treat. The model is based on the original mole fraction model for the $(NH_4)_2SO_4$-H_2SO_4-H_2O system developed by Clegg, Pitzer and Brimblecombe (1992). The first phase of the

program consists of expanding the model to include the effects of Na^+, NO_3^-, and Cl^-. The new model will be able to predict aerosol acidity and liquid water contents, aerosol concentrations of NH_4^+, Na^+, Cl^-, NO_3^-, HSO_4^-, and $SO_4^=$, and gas phase concentrations of NH_3, HNO_3, and HCl. In 1996, model predictions will be compared with particulate field data and the model refined, if necessary.

6. Regional Particulate Model and Planned Improvements

The EPA is developing an air quality model to look at visibility. The Regional Particulate Model (RPM) is specifically designed to model regional haze. This model is a three dimensional Eulerian air quality simulation model. The final stage of model development will have multicomponent aerosol particles consisting of sulfates, nitrates, elemental and organic carbon, and soil derived components. Atmospheric chemistry will consist of gas-phase and aqueous-phase chemistry both in cloud droplet water and in hydrated aerosols, as well as wet and dry deposition of gases and particles. The model is an extension of the Regional Acid Deposition Model (RADM) developed for the National Acid Precipitation Assessment Program (NAPAP). The transport, gas-phase and aqueous-phase cloud water chemistry, and wet deposition are the RADM portion of RPM and have been extensively exercised and reviewed by an international peer review panel whose recommendations for improvements have been incorporated into the current version. The extensions include explicit representation of particle size distributions (as lognormals), aerosol dynamics (coagulation and growth), cloud scavenging and aqueous production of new aerosol material, size-dependent dry deposition, and wet deposition.

The current status of the model is as follows. A first generation version has been developed which includes the size distribution and aerosol dynamics with size-dependent dry deposition but only for primary and secondary sulfates. This model includes equilibration with relative humidity and neutralization by gaseous ammonia. By fall 1994, the model is planned to also include a representation of cloud-aerosol interactions commensurate with the representation of clouds in RADM. This will complete the first generation version of RPM. By fall 1995, nitrates, organics, and elemental carbon are planned to be added to the model. This can be accomplished relatively easily because of a related model which has all of these species but no representation of the particle sizes. This model has been used to study aerosol impacts in the metropolitan Denver area (Middleton, 1993). A module to address the larger, or coarse model, particles is planned to be added by spring 1996. RPM is being integrated into the EPA's next generation (Models 3) system and all future improvements to other parts of the system are planned to be incorporated into RPM when available.

Model output was used to make an estimate of Koschmieder visual range using three approaches, Mie extinction, an approximate method based on Mie extinction but which uses particle properties such as size distribution and index of refraction, and an empirical parameterization based upon total aerosol mass (Hanna et al. 1993). The results show that the combination of model output from RPM and a simplified extinction coefficient produces estimates of visual range consistent with regional analyses of visibility observations.

Precise numerical calculation of the path radiance resulting from complex multiple scattering processes requires a large number of computations, particularly for regional visibility modeling applications. Using the results of an optical measurements and analysis program, an approximate technique to estimate the atmospheric path radiance and directional contrast transmittance will be used to calculate the vertical distribution of the atmospheric attenuation and single and multiple scattering phase functions. Results will be compared with calculations from Mie theory and other approximate algorithms that are used to calculate light extinction. The RPM uses bimodal lognormal distributions to characterize aerosol sizes and will provide regional aerosol size distributions over the eastern United States. The optical properties of aerosols using different algorithms will be used to estimate the regional visibility.

It is recognized that regional scale Eulerian based air quality models that do not explicitly treat the details of major point source pollutants within their grid system misrepresent their contribution and can distort predicted deposition and concentration patterns. With the advancement of nesting procedures, models are becoming able to resolve such features. However, as a matter of practical concern, i.e., until computational power increases significantly for general users, and until the details of dispersion and near source chemistry are better understood, simplified ad hoc approaches for modeling these sources are currently used. The EPA and North Carolina State University started a three-year collaboration in reactive plume modeling. This technical effort is intended to develop and test a point source model that will treat its chemical and dispersion evolution from near source to distances at which a grid model can resolve and handle the remaining details. A final report is expected in 1996.

A new competitively selected cooperative agreement is planned to begin before October 1994 to address plumes. The primary objectives of this 2-year cooperative agreement are to explore and to evaluate various reactive plume modeling approaches, and to determine innovative techniques for coupling reactive plume modeling systems in multi-grid modeling frameworks. This effort will attempt to advance plume dispersion and chemical processes of different state-of-science reactive

plume models systems in order to identify and to recommend a set of scientifically realistic and reliable plume modeling techniques for use in air quality grid models.

The EPA in-house investigations continue with the objective of developing methodologies for improving the parametric formulation for the aqueous chemistry component of the Calpuff model. The interest is for situations when puffs are impacted by low level clouds, and for determining when and where such clouds are juxtaposed with the puffs.

7. Source Attribution with Trajectories

The EPA is supporting research to investigate source areas of both clean air and of air arriving on days with severe haze. This Clean Air Corridor research is funded through an interagency agreement with NPS. In addition, a competitively selected cooperative agreement is planned to start October 1994 to further develop user friendly trajectory models on a PC platform.

8. Aerosol Modeling

New research is planned to begin before the end of September 1994 in the area of aerosol modeling. The cooperative agreement was competitively selected and has several objectives. The first objective is to explore flexible methodologies of applying current aerosol modeling capability to more accurately represent relevant chemical and dynamical processes from regional to urban scales. It will use expanded representation of inorganic aerosol thermodynamics which recognizes presence of mixed solid-aqueous particles.

The cooperative agreement will investigate the use of more efficient mathematical algorithms to represent the thermodynamics of aerosol chemical systems. Finally, the research will explore use of parallel computers to increase speed of aerosol models.

9. Other EPA Studies Under Sections 812 and 404 of the 1990 CAAA

Section 812 of the 1990 CAAA calls for EPA to analyze the impact of the Clean Air Act (CAA) on the public health, economy, and environment and, in performing such analysis, to consider the costs, benefits and other effects associated with compliance with standards issued for specified programs. The report will likely include valuing increases in visibility attributable to the CAA.

The literature draws distinctions in the methodology for assessing visibility-related benefits between valuation of visibility in the eastern U.S. and western U.S. and is based on evidence that the physical qualities of visibility in the East are fundamentally different from those in the West. On average, willingness-to-pay for a given percentage change in visibility is

higher in eastern cities. Cropper and Oates (1991) in a survey of environmental economics concluded that visibility benefits vary regionally and should be classified according to whether the locations studied are in the eastern or western U.S. Chestnut and Rowe (1992) state:

> "Because of differences in the characteristics of landscape, natural background visibility conditions, and visual air pollution impacts, we judge that, for this application [valuing visibility improvements in the eastern U.S.], studies conducted only in the eastern United States should be used for quantification. Studies conducted in the western United States might provide some useful information that would help interpret some of the eastern studies, such as the relative importance of health concerns versus visual aesthetics when respondents give WTP [willingness-to-pay] estimates for improvements in air quality."

Research contributing to this report is being compiled by Industrial Economics, Incorporated. The retrospective report for costs and benefits 1970-1990 should be available late in 1994. A prospective report on costs and benefits 1990-2030 should follow in late 1995.

EPA is currently working to complete the Acid Deposition Standards Study called for under §404 of the 1990 CAAA. The purpose of this study is to assess the feasibility and effectiveness of setting and implementing a standard(s) to protect sensitive and critically sensitive aquatic and terrestrial resources from acidic deposition. The study integrates state-of-the-art ecological effects research, emissions and source-receptor modeling work, along with implementation and cost issues.

The study will identify sensitive ecosystems and determine the environmental impact of acidic deposition levels after implementation of the CAA, including the sulfur dioxide emissions trading program, and varied levels of sulfur and nitrogen deposition. The study's quantitative assessment focuses on surface water effects. However, a standard and potential emission reductions may impact visibility, particularly in the eastern U.S. and this will likely be examined. Finally, the study will identify and discuss approaches to and issues related to implementing an acid deposition standard.

IV.C. National Park Service (NPS)

The NPS supports research in visibility monitoring with

three distinct components: view (scene) monitoring; electro-optical monitoring; and aerosol monitoring.

Combining the results of these three monitoring components yields an understanding of how the appearance of a scene is influenced by the way light is transmitted through the combination of aerosols present in the ambient atmosphere. There are 30 IMPROVE sites along with 14 additional NPS sites designated to be operated according to IMPROVE Protocol.

The NPS supports monitoring related research on the IMPROVE. Many of the results have been published. There is currently research on SO_2 collection, nitrate loss on Teflon filters, Teflon-nylon comparisons of sulfate with very high loadings, summer soil episodes in the eastern United States and geographical patterns of trace elements.

The Shenandoah study, conducted during the summer of 1991 at Shenandoah National Park, was performed to test agreement between optical instruments (nephelometers and transmissometers), examine sulfate aerosol acidity, and apportion light extinction to various aerosol species. The Penn State Study was conducted at Scotia State Wildlife Preserve during the summer of 1991. This study was designed to closely examine sulfate aerosol acidity by examining neutralization of acid sulfate particles during sampling, comparing various methods of determining sulfate aerosol acidity, and comparing the UC Davis IMPROVE sampler to Harvard's HEADS sampler. Results of this study show how some neutralization of acidic particles can occur during sampling, the direct measure of ammonium ion is the best method for determining sulfate particle acidity, and the IMPROVE sampler agreed well with Harvard's HEADS sampler.

Research in the past year has focused upon development of improved understandings of factors influencing visibility in Shenandoah National Park. Comparisons between the Harvard and IMPROVE methods for determination of the degree of sulfate neutralization showed that the degree of sulfate neutralization may be overpredicted in some instances, resulting in underestimates of the sulfate contribution to scattering.

Impactor-derived sulfate mass distributions, along with corrected acidity estimates and water uptake estimates, were used in a Mie scattering model. The computed scattering coefficients were compared with estimates using statistically-derived mass scattering coefficients with nephelometer data. Computed b_{scat} values were consistently lower than expected from the measurements, which may suggest that water uptake departs significantly from theoretical values. Possible reasons for such departure include nonideality of mixtures and kinetic limitations (e.g., the effects of an organic coating) to particle response to shifts in ambient humidity. The possibilities are currently being

explored from a theoretical standpoint.

The scattering model was applied to the systematic investigation of the effects of composition, relative humidity, mass mean diameter, and standard deviation of the aerosol population upon computed scattering coefficients. For the cases examined thus far (ammonium sulfate), assumption of geometric standard deviation near 1.5 can significantly enhance the predicted scattering, relative to the statistically-derived values; however, it is not clear that such geometric standard deviations are realistic. The computational investigation underscored the need for better-resolution size distribution measurements during special studies, including measurement of wet and dry distributions; in addition to assisting in the modeling of scattering, shifts in the mass distribution that are *not* due to humidity changes could then be ascertained and possibly related to meteorological conditions. This work is continuing, and will explore more acidic compositions and also internal mixtures.

A study in the Great Smoky Mountains National Park during the summer of 1994 was designed to further investigate these issues. The measurements include: assessment of ambient aerosol's bulk chemical composition, aerosol size distribution (by mass and number concentrations), light scattering by ambient aerosol and by fully neutralized sulfate aerosol, and the monitoring of meteorological conditions.

The information obtained from this study will be used to formulate models which are able to predict light extinction from mass of ambient aerosol. This is a first step to developing a model which can accurately assess light extinction directly from emissions data.

The backward Monte Carlo radiative transfer code used in the visibility modeling effort of the NPS was modified to include absorption by the atmospheric trace gases O_3 and NO_2 at arbitrary wavelengths in the visible region of the electromagnetic spectrum. The program allows for enhanced concentrations of these gases below the mixing layer or in plume-like structures, or both. A theory and computer program for the calculation of the light scattering properties of sphere aggregates, including cross sections for total scattering, absorption and extinction, have been developed and made available to the NPS. A theory for light scattering by spheres possessing arbitrarily placed spherical inhomogeneities has been derived, along with a new, very efficient algorithm for calculating the scattering properties of concentrically stratified spheres. Sphere aggregates and inclusions are being studied in order to better understand the optical properties of both externally and internally mixed soot. Version 1.0 of AGEACT (Aerosol and Gas Effects on Atmospheric Contrast Transmission), an operational

model for visual air quality impact studies is expected to be released by summer of 1995.

Work is expected to proceed on refinements to the AGEACT model and on the optical properties of internally mixed aerosol particles. A study, based on exact calculations for densely packed sphere aggregates, of possible enhancements of absorption by carbonaceous particles in densely packed filter samples relative to absorption of free carbon has also been proposed. A theoretical investigation of Muller matrices, albedos and asymmetry parameters of haze particles possessing internal structure, such as sulfate-coated soot aggregates is also underway. Preliminary work with quasi-Monte Carlo methods has produced a substantially faster forward Monte Carlo algorithm that will be applied to the study of upwelling flux from atmospheric haze layers. This is in connection with questions regarding climatic effects and remote sensing of particulate pollution. The radiative transfer and sphere aggregate work is being combined in a study of the possible effects that various forms of atmospheric carbon have on visibility and climate.

The NPS is supporting nonlinear regression modeling using the differential mass balance model for the MOHAVE winter data. This work attempts to explain simultaneously both $SO_4^=$ and SO_2 concentrations at Hopi Point using the differential mass balance model. A by-product of this method will be an apportionment analysis giving ranges of daily contributions of $SO_4^=$ from specific sources to Hopi Point. This work is computer intensive but results obtained so far suggest that this method holds promise. Eventually, it would be of interest to consider summer data as well. Also, it would be of interest to consider simultaneous multiple receptors. Loglinear modeling of data obtained from psychophysics experiment, to evaluate subjects' ability to remember haze levels over a 24-hour period indicates that satisfactory models can be constructed to explain the experimental data.

The NPS is one of the sponsors of Project MOHAVE. Spatial and temporal patterns in particle data are being studied. Fine particle data were collected at approximately over 30 sites during each of the MOHAVE intensive periods. These two periods were mid-January to mid-February 1992 and mid-July through early September 1992. Spatial and temporal patterns in these data are being examined graphically by time lines and spatial contours and analytically by summary statistics, inter-site and inter-species correlations, and empirical orthogonal function analysis.

Animations of spatial patterns are being prepared. By linearly disaggregating the 12-hour average particle concentrations to 1-hour averages, enough frames of spatial contours can be developed to animate the spatial patterns in the data. The resulting video tape aids visualization of the data.

Rough drafts of the videos for sulfur, organics, elemental carbon, bromine, lead, and selenium are in various stages of completion. Eventually, wind vectors will be overlaid on the contours.

Trajectory models are being compared by NPS. Some simple intercomparisons between two back trajectory models are being conducted. The two models are ATAD, a simple 1-layer lagrangian puff model and a model developed at the Washington University, which is currently being called the "NGM Model" because it uses gridded wind fields provided by the NWS's NGM forecast model. The ATAD has the advantage of being simple and inexpensive enough to simulate many years of back trajectory estimates. This is useful for putting the MOHAVE time period in historical context. The NGM model has several advantages including 3-dimensional rather than 2-dimensional trajectories, the ability to carry along several useful variables such as temperature, particle height, relative humidity, etc., simulation of dispersion.

The first draft of a report examining source attribution of all species measured at Grand Canyon National Park during 1989-1991 has been completed. The report includes the results of approximately a dozen different back trajectory techniques applied to several particulate species. Data for 1992 and 1993 may also be added. This report may be either a stand-alone report or be incorporated as part of a larger report to the Grand Canyon Visibility Transport Commission or included as historical information in the Project MOHAVE Report.

Examination of "clean air corridors" using several back trajectory techniques is in progress. Clean air corridors have been defined as areas which supply "clean" air masses to a receptor. Clean has been defined by the emissions subcommittee of the Grand Canyon Visibility Transport Commission as the best 20% of the b_{ext} measurements at a given receptor site. Current plans are to examine data from Grand Canyon, Petrified Forest, and Canyonlands National Parks. Back trajectory techniques will be used along with IMPROVE particle data from Big Bend National Park and Chiricahua National Monument to identify source areas and estimate emissions in Mexico.

Data from project MOHAVE was used to investigate the relationship between optical absorption and measured carbon. Absorption was estimated by two independent methods. One method, referred to as thermal optical reflectance (TOR), relied on collecting aerosol samples on quartz substrates and measurement of evolved carbon as the sample was heated in an oven. "High temperature" carbon is assumed to be elemental and light absorbing. A second technique, the laser integrated plate method (LIPM), relied on collection of aerosols on Teflon filters and subsequent direct measurement of absorption by optical techniques. Extinction was measured with long path

transmissometers, while ambient scattering was measured with "open air" integrating nephelometers. Coarse (2.5-10.0 μm) and fine (less than 2.5 μm) mass and associated aerosol species were measured using standard size segregators and analytic techniques.

Comparison of extinction, scattering, and absorption measurements strongly suggest that optical absorption by TOR underestimates optical absorption by a factor of approximately two, while absorption by LIPM is more closely in agreement with measurements of extinction. It also appears that coarse mass scattering may have been underestimated by approximately 30%. Historically, extinction budgets have been calculated using thermal optical techniques to estimate absorption. New extinction budgets are calculated for remote areas of the United States using optical absorption as estimated by LIPM and comparing them to the more traditional methods using TOR. When using LIPM to estimate absorption, carbon-derived scattering and absorption are shown to be responsible for 40-50% of the extinction at most remote western monitoring sites.

Models to reconstruct absorption using data from IMPROVE need to be evaluated. Uncertainties in the formulation of reconstructed fine aerosol mass revolve around the TOR carbon data. In particular, the identification of light absorbing carbon as well as the artifact correction need study. Resolution of the best reconstruction of aerosol mass is, of course, closely tied to reconstructed aerosol extinction. Specifically, models that reconstruct absorption as measured by LIPM using IMPROVE aerosol, optical, and detailed carbon data need to be presented.

A reconstruction requires the use of optical efficiencies. These are not known, but have been estimated. Determination of acceptable values is critical and will play an important role in the quality of the reconstruction.

Given the best reconstruction from IMPROVE, a spatial and temporal characterization of visibility and aerosol conditions for the United States will be presented. The characterization will describe the range of conditions found and the probabilities of occurrence.

Other issues relate to aerosol acidity and solubility and the need for more realistic models of aerosol size distributions and mixtures. Analysis of the effects of size distributions for ammonium sulfate on scattering have been carried out. Next to be investigated are scattering by acidic sulfates, ammonium nitrate, and organics. The more difficult problems of mixtures also need to be considered. Work in this area will be limited to literature searches and discussions with other researchers.

IV.D. Department of Energy (DOE)

The DOE initiated a Visibility Assessment Program in 1990 as an extension of its general environmental assessment activities. The research is directed toward maintaining assessments of environmental and economic benefits of energy supply options.

Initial efforts have used the Argonne National Laboratory ASTRAP lagrangian model and the DOE Visibility Assessment Scoping Model (VASM). Updated emissions data bases have been used and sensitivity analysis performed with respect to assumptions, uncertainty in aerosols and variability in climate.

During the 1994-1995 period the research focus includes: organic aerosol high humidity growth; relative contribution to organic aerosols of fossil versus biogenic; and models. The models development will provide an easier to use update to VASM, the optics model for assessments. The ASTRAP will have specific regional versions and will incorporate fine particulate transport.

The Atmospheric Radiation Measurement (ARM) Program conducts some visibility-related research in DOE. Visibility related research includes the four-dimensional data assimilation and the relationship between aerosols and clouds.

The ARM Program has two basic objectives: 1) to improve the treatment of radiative transfer in climate models under all relevant conditions, and 2) to improve the treatment of clouds in climate models, including the representation of the cloud life cycle and the prognosis of cloud radiative properties. The approach of the program is to establish measurement facilities at key climate-sensitive locales to acquire measurements of atmospheric radiative properties (solar irradiance, longwave fluxes), atmospheric state, and distributions of key radiatively-sensitive atmospheric constituents, such as water vapor, aerosols, and radiatively-important trace gases. One aspect of the measurement program that is related to visibility impairment studies is solar irradiance measurements obtained with the Multi-Filter Rotating Shadow and Radiometer (MFRSR). These measurements can be used to determine direct-to-diffuse irradiance ratios and aerosol optical depths at several wavelengths. Estimates of boundary layer height from various profilers, including lidars and sodars, can in turn be used with the optical depth measurements to infer a mean boundary layer aerosol extinction coefficient. Aerosol light scattering measurements are also obtained at the surface. These quantities are all related to traditional visibility impairment measures.

The DOE will prepare periodic assessment reports that evaluate national, long-term visibility alterations that arise from changes in the emissions of SO_2, NOx, and VOC resulting from

different energy supply scenarios of the National Energy Strategy and CAAA of 1990. They will characterize aerosol light extinction and visibility over an annual cycle at a variety of locations in the United States by explicitly treating variable aerosol chemical composition and relative humidity effects. The characterization is performed for current conditions using available data bases and aerosol optics models and is being applied to potential future emissions conditions using regional model simulations and other process-related models to estimate changes in aerosol chemical composition and mixing characteristics as chemical components are removed from the system. They will provide an estimate of visibility impairment distribution curves for non-energy background conditions for comparison with curves obtained for the various emission change scenarios. This project depends on data collected by other projects for improving quantitative relationships among measured aerosol light extinction (and/or visibility), size-resolved aerosol chemical species concentrations, and relative humidity. The project also provides a modest contribution to augment ongoing aerosol optical characterization field studies.

Three workshops have been convened to frame the technical and policy-needs aspects of a visibility impairment program plan. The first workshop defined the technical basis of the assessment. The workshop participants recommended the use of empirical relationships between aerosol characteristics and light extinction in the preliminary assessment and proposed several options for performing the later assessments. In the second workshop, the participants reviewed progress in the development of the assessment plan from the context of policy information needs of various federal agencies and other organizations. The third workshop focused on the role of background aerosol in determining visibility impairment. A preliminary assessment report was drafted in late 1992 using currently available relationships between aerosol mass concentrations, relative humidity and light extinction and existing data bases (e.g., NPS IMPROVE Network data was used for aerosol concentrations and visibility, while the NOAA Local Climatology reports and other IMPROVE data sets were used for relative humidity and temperature) to establish a baseline for current conditions at Shenadoah National Park. Recent aerosol thermodynamic equilibrium and Mie-scattering models and algorithms were adapted for use in the assessment process and were checked with available monitoring and high-resolution field data.

An assessment report for 1994 using results generated with the new models for both current conditions and reduction scenarios based on the 1990 CAAA for Shenandoah and Grand Canyon National Parks is in preparation. Additional locations, which presently are deemed important for assessment studies, are being selected for analysis with the assessment models. In addition, the role of organic carbon aerosol, as well as that of elemental

carbon, to visibility impairment, relative to that produced by sulfate and nitrate aerosol is being examined with models and with available field data. Methods for distinguishing organic carbon originating from natural processes and energy-related emissions is a key feature of these studies. Finally, regional-scale atmospheric transport and chemistry models will be used to establish uncertainty limits of the assessment procedure and results. The project will also support two Russian aerosol scientists, under the auspices of the Department of Commerce Special American Business Internship Training (SABIT) Program, to provide technical expertise in the areas of aerosol formation processes and data analysis and interpretation.

The DOE is using technology developed for DOE prototype instruments to fabricate a multi-filter rotating shadowband radiometer (MFRSRs). The MFRSR measures total and diffuse horizontal irradiance, and from the difference and with solar ephemeris data, computes the direct normal irradiance. The rotating shadowband is configured for mid-latitudes (20-55 degrees). The NOAA, Colorado State University, and National Institute of Science and Technology instruments have a central detector with a broadband ultraviolet-A (UVA) detector. An additional latitude bracket is required for use in tropical areas.

Battelle and the State University of New York at Albany will commercialize the single and multiple wavelength versions of the rotating shadowband radiometers. A commercial vendor (Yankee Environmental Systems) was licensed to manufacture these instruments in June 1993. The same detector is used for the measurement of both total and diffuse irradiance and thus allows a precision in calculating the direct normal irradiance approaching or exceeding sun-tracking radiometers. Direct-to-diffuse irradiance ratios do not need an absolute calibration of the detectors. Extraterrestrial solar constants and total optical depths can also be computed for each wavelength channel using the Bouguer-Beer-Lambert attenuation law and the direct normal irradiance as a function of time of day or atmospheric airmass thickness.

The DOE is investigating how clouds interact with longwave (infrared) and shortwave (solar) radiation to regulate the heating of the planet. As mentioned earlier, this is a central issue in the radiatively forced global climate change issue.

Clouds mask about half the earth's surface at any given time. Therefore, it is important to know how clouds interact with outgoing longwave (infrared) and incoming shortwave (solar) radiation to regulate the heating of the planet. To better understand how these climatically opposed effects vary in time, with cloud type and structure, and, to a limited extent, with geography, there is a nine-station regional network in the

eastern United States and each station is equipped with standard instruments for measuring ambient temperature, total precipitation, and relative humidity. Observations of diffuse horizontal, total horizontal, and direct normal solar irradiance are the primary solar measurements and are made with a MFRSR in six narrow-wavelength bands and one unfiltered broadband that corresponds to the standard shortwave instruments. For increased stability and reliability, all three solar radiation components are determined with the same sensor for each wavelength band. Several climate-sensitive parameters, derived from the solar observations, include cloudiness, cloud optical depth, cloud type (to some extent), and aerosol optical depth and its wavelength dependence. The goals of this 5-year study, in order of emphasis, are: 1) to use ground-based measurements in concert with the satellite results to characterize cloud radiative forcing for a variety of cloud types and structures over a limited geographical area; 2) to track changes in cirrus frequency and optical depth; and 3) to track changes in aerosol optical depth and its wavelength dependence.

The nine-station Quantitative Links Network (QLN) has been in operation since late 1991 with a 90% data recovery rate. A major activity during FY 1993 was the development of data reduction and analysis methods, including routines to: (1) perform cosine response corrections on the direct irradiance data, (2) perform automated Langley regressions to calculate aerosol optical depths and calibration constants for the six filtered detectors, and (3) apply general calibration algorithms to produce engineering data.

IV.E. Electric Power Research Institute (EPRI)

The EPRI is not a government entity, but heavily invests in research coordinated with both governmental and non-governmental organizations in a number of cooperative efforts: visual air quality and climatology in the inter-mountain West; observational methods; laboratory and theoretical investigations of particles in their suspended state; human visual perception of changes due to aerosol; computer models of regional, local and plume effects; risk analysis models coupling physical and physiological sciences with socio-economic costs and benefits of emission options. Much of the research is overlapping with other atmospheric issues. For example, particles are of interest because of the health issue when they are inhaled, as well as being of importance in visibility. The radiative balance affects visibility as well as climate change.

To determine the impact of emissions on visual air quality, EPRI research addresses four logical relationships: (1) emissions to aerosols, (2) aerosols to atmospheric optics, (3) optics to human perception, and (4) perception to socio-economic values and policy options. The atmospheric sciences focus is on the first

three steps, which lead from emissions to human perception. This involves studies of the relationship between visibility and the physics and chemistry of the atmosphere, including the seasonal and geographical variability in visual air quality.

The EPRI's current plans for research are aimed at a potentially cofunded project to study these topics in the southeastern United States as a continuation of cofunded projects carried out in the inter-mountain West since 1982.

The aerosol chemistry and physics part of EPRI's work deals with issues of importance to atmospheric aerosols: namely the nature of the particles in their suspended state. The suspended state of the particles tends to be modified when they are collected on filters or other surfaces. For example, atmospheric particles absorb water as relative humidity increases and lose water when it decreases. Previous work on particulate water content has focused largely on inorganic components (sulfates, nitrates, etc.) for which hygroscopic properties are known. Recent EPRI-supported work shows that water-soluble organics, as well as the configuration of internally mixed particles, also play important roles in determining water content and optical characteristics. Both theoretical and experimental work is continuing so that these phenomena can also be represented in numerical simulation models.

Research in the southwestern U.S. has improved the understanding of the climatology of aerosol concentrations in the region, and their relation to visibility. In evaluating the contribution of carbon and sulfate to particle concentrations, the important role of wind blown dust, less than 2.5 μm in diameter, was identified.

The aerosol optics part of EPRI's research applies light scattering theory to measured aerosol size distributions to determine the contributions of the major fine particle components to extinction, and to determine the improvement in visibility that would be expected if the concentration of a given species were reduced by a specified amount. Previous EPRI-supported work raised questions about multiple linear regression (MLR) analysis, which is subject to errors associated with variability in aerosol size distributions and sampling errors for organic carbon. EPRI supported a study of aerosol optical properties in the southwest desert during the summer of 1992 in which theoretical methods were used to evaluate component optical properties based on measured size distributions. In the EPRI-supported work aerosol water content and mixing characteristics are based on size-resolved measurements. Optical calculations are based on Mie theory. Statistical assumptions underlying the MLR were not necessary.

Models for human visual response continue to be evaluated. Many previous studies of human perception have taken place in the western U.S. with diurnal conditions of low and high humidities and low extinctions. In the eastern U.S. the extinction of suspended particle concentrations is much higher and high humidities are of much longer duration, giving rise to shorter vistas with much more apparent haze than in the West. In the East, and to some extent in the West, perceived colors and contrast by human observers remain to be compared with physical measurements and model calculations. Radiative transfer models used to create simulated photographs for estimating visibility impacts for specified aerosol loadings should be evaluated against actual radiance from key scene elements as perceived by human observers. EPRI developed hardware provides procedures for digitizing actual human perception of vistas by relating them to their photographs.

Laboratory research is planned to develop new measurement methodologies for parameters of importance for atmospheric aerosols. A method for direct measurement of time-resolved aerosol water content and a portable instrument for measuring aerosol optical absorption coefficients are included.

Diagnostic evaluation of algorithms inside of models is important because future, comprehensive mathematical models will be used to determine relationships between natural and manmade emissions and atmospheric particulate concentrations. Work on developing and testing such models is already underway in, but not limited to, support of the GCVTC.

Finally, work is underway to develop models capable of coupling the climatology of atmospheric aerosols, aerosol precursor emissions, cost of various emission management options and the benefits in terms of improved community health and visibility within a risk analysis framework.

IV.F. National Oceanic and Atmospheric Administration (NOAA)

Visibility related research at NOAA continues to be related to the implementation of the new Belfort visibility sensor, a component of the ASOS. The sensor will not necessarily have good correspondence with human observations which may be limited for other reasons. The sensor may provide an indication of higher or lower visibility than the human observer. The human observer tends to see over the haze layer at high visibilities. Because of the earth's curvature, the observer is not able to see distant targets within a thousand feet of the surface and the observer will report higher visibility than the sensor. The criteria being used for evaluation of this sensor is not in agreement with human observations, but it does provide sufficient information for aviation safety. Thus the location of sensor and other considerations may lead to measurements that do not agree with

human observations, but are better for the safety of aircraft. Research continues to determine the visual range which can be estimated with the Belfort visibility sensor.

The NOAA also has visibility related research that is part of the global change program. Marine aerosols are the focus. A Southern Hemisphere Marine Aerosol Characterization Experiment will be conducted November-December 1995. The goal is to document chemical, physical and optical characteristics of the aerosols and determine the controlling processes of aerosol in the remote marine atmosphere. Later, a second phase will examine the marine atmospheric gas/aerosol systems over the North Atlantic Ocean with a focus on anthropogenic perturbation of these systems.

V. Concluding Remarks

There has been continued research in visibility and related scientific areas. As indicated in the preceding discussion, more results are expected in the next few years. However, Federal visibility research resources will likely change in the near future.

V.A. EPA/Office of Research and Development (ORD) Plans to Eliminate Funding of Exclusively-Focused Visibility Research

The EPA/ORD plans to fund the research presented in Section IV. The EPA/ORD currently does not plan to fund additional research focused exclusively on visibility.

V.B. EPA/ORD to Fund Particle Research which Includes Visibility Implications

Atmospheric particles are of important human health concern. Particle research, including size and composition, is a priority at EPA. Much of the science that is developed on particles in urban or suburban environments is relevant to visibility in highly populated areas and can also be utilized for Class I areas. In particular the regional aspects are baseline to both human health and visibility.

V.C. Regional Haze Regulation

Mary Nichols, EPA Assistant Administrator, Office of Air and Radiation, testified April 29, 1994, before the U.S. House of Representatives' Subcommittee on Environment, Energy, and Natural Resources of the Committee on Government Operations. In her written testimony, she stated that EPA plans "to initiate the technical activities needed to analyze the appropriate scope and components of a regional haze rulemaking." The most immediate effort will develop models and monitoring techniques for regional

planning. The EPA will consider options for addressing regional haze impairment in all Class I areas. The options will be informed by recommendations in the report of the Grand Canyon Visibility Transport Commission, due November 1995, and the work of the Southern Appalachian Mountains Initiative.

EPA's written testimony indicated that full implementation of the next phase of the acid rain control program will be a major step in improving visibility in Eastern class I areas and reducing deposition-related damage. EPA also indicated that after full implementation of the acid rain program, there will be the need to have other programs to assure reasonable progress towards the Congressionally established national visibility goal to prevent future and remedy existing manmade visibility impairment in mandatory class I Federal areas. EPA's testimony indicated that although the NRC (1993) report stated that there is still some uncertainty regarding the relationship between human activities and visibility, NRC (1993) reported that the basic science needed to address regional haze is now available. EPA indicated that it intended to develop the technical tools to address regional haze based on the scientific foundation presented in the NRC (1993) report.

V.D. CENR Subcommittee on Air Quality Research

President Clinton's National Science and Technology Council has a Committee on Environment and National Resources (CENR) which contains a subcommittee on Air Quality. This subcommittee has the responsibility to consider visibility issues and identify the research necessary to address policy questions. This subcommittee looks across Federal agencies and considers the full spectrum of research and needs related to visibility. Changes and new efforts are planned by individual agencies for FY96 and beyond. However, the programmatic milestones and schedule contained in the CENR draft implementation plan extend only to the fall of 1995.

V.E. Global Change Research

Global change research has addressed aerosols, but not because of visibility concerns. Aerosols are an important component in radiative forcing. The IPCC (Intergovernmental Panel on Climate Change) is preparing a report on "Climate System Radiative Forcing". Chapter 3 of that report deals with aerosols and Chapter 4 with radiative forcing. This report is not available for attribution at this time. Much of the atmospheric chemistry research related to aerosol effects that is important for the climate system is also relevant to visibility research.

V.F. Continuing Research

A review of research in progress and planned as presented in

Section IV of this report indicates that research will be continued in visibility related areas. The research is spread across a wide spectrum of entities. Communication and cooperation are essential to assure quality research and data.

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APPENDIX A: ACRONYMS

ADS	Annular Denuder System
AGEACT	Aerosol and Gas Effects on Atmospheric Contrast Transmission
ANL	Argonne National Laboratory
AQRV	Air Quality Related Values
ARM	Atmospheric Radiation Measurement
ASASP	Active Scattering Aerosol Spectrometer Probe
ASOS	Automated Surface Observing System
ASTRAP	Advanced Statistical Trajectory of Regional Air Pollutants
ATAD	Atmospheric Transport and Diffusion Model
CAA	Clean Air Act
CAAA	Clean Air Act Amendments of 1990
CALMET	CALifornia METeorological Model
CAPITA	Center for Air Pollution Impact and Trend Analysis
CAPTEX	Cross-APpalachian Tracer EXperiment
CASTNET	Clean Air Status and Trends Network
CENR	Committee on Environment and National Resources
CSU	Colorado State University
CVN	CASTNET Visibility Network
DOD	Department of Defense
DOE	Department of Energy
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EQUILIB	EQUILIBrium code (Atmos. Environment, 21(11):2453-2466 (1987)
FAA	Federal Aviation Administration
GCVTC	Grand Canyon Visibility Transport Commission
HEADS	Harvard-EPA Annular Denuder Systems
HOCS	Human Observer Comparison Study
HY-SPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectories
IPCC	Intergovernmental Panel on Climate Change
IMPROVE	Interagency Monitoring of Protected Visual Environment
IWAQM	Interagency Work Group on Air Quality Modeling
LIPM	Laser Integrated Plate Method
MESOPUFF	MESOscale Lagrangian PUFF dispersion model
MFRSR	Multi-Filter/detector Rotating Shadowband Radiometer
MLR	Multiple Linear Regression
MM4-FDDA	Mesoscale Meteorological Model - Version 4 - Four Dimensional Data Assimilation
MOHAVE	Measurement of Haze and Visual Effects
MUSCAT	MUltiple SCATtering
NAPAP	National Acid Precipitation Assessment Program
NGM	Nested Grid Model
NIST	National Institute of Science and Technology
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NRC	National Research Council
NWS	National Weather Service
ORD	Office of Research and Development
PSD	Prevention of Significant Deterioration
QLN	Quantitative Links Network
RADM	Regional Acid Deposition Model
RAMS	Regional Atmospheric Modeling System
RH	Relative Humidity
RPM	Regional Particulate Model
RSR	Rotating Shadowband Radiometer (also "Rotating
SABIT	Special American Business Internship Training (SABIT)
SCE	Southern California Edison
SCENES	Subregional Cooperative EPA, NPS, and Electric Utility Study
TOR	Thermal Optical Reflectance
UC-Davis	University of California at Davis
UNC-CH	University of North Carolina - Chapel Hill

UVA	Ultraviolet-A
VARED	Visibility Assessment of Regional Emission Distributions
VASM	Visibility Assessment Scoping Model
VOC	Volatile Organic Compound
WTP	Willingness to Pay

Appendix B

Measured fine and coarse aerosol concentrations (in $\mu g/m^3$) for the 19 regions in the IMPROVE network, averaged over the three-year period, March 1988 through February 1991. (Sisler, Huffman and Latimer, 1993).

Season	Fine Mass	Sulfate	Nitrate	Organics	Elemental carbon	Soil	Coarse Mass
ALASKA							
Winter	1.6	0.7	0.1	0.6	0.1	0.2	4.0
Spring	2.4	0.9	0.1	0.7	0.1	0.6	3.9
Summer	2.7	0.5	0.0	1.5	0.1	0.4	5.4
Autumn	1.2	0.4	0.1	0.6	0.1	0.1	3.2
ANNUAL	1.9	0.6	0.1	0.9	0.1	0.3	4.2
APPALACHIAN							
Winter	6.5	3.0	0.8	2.0	0.4	0.3	3.1
Spring	10.6	6.0	0.8	2.7	0.5	0.6	4.5
Summer	16.6	6.0	0.3	4.4	0.5	0.8	11.2
Autumn	9.7	5.6	0.5	2.7	0.5	0.4	5.5
ANNUAL	10.9	6.3	0.6	3.0	0.5	0.5	6.2
BOUNDARY WATERS							
Winter	5.2	2.0	1.4	1.4	0.2	0.2	3.2
Spring	5.4	2.6	0.4	1.8	0.2	0.4	5.1
Summer	6.2	2.2	0.1	3.1	0.3	0.5	8.2
Autumn	4.3	1.6	0.4	1.8	0.2	0.3	5.8
ANNUAL	5.3	2.0	0.6	2.1	0.2	0.3	5.7
CASCADES							
Winter	3.8	0.6	0.1	2.6	0.5	0.1	2.9
Spring	5.2	1.4	0.2	2.7	0.5	0.3	3.1
Summer	6.7	2.4	0.4	3.0	0.5	0.3	4.6
Autumn	5.3	1.3	0.2	3.1	0.5	0.2	3.9
ANNUAL	5.1	1.3	0.2	2.8	0.5	0.2	3.5
COLORADO PLATEAU							
Winter	2.9	0.9	0.5	1.1	0.2	0.3	3.2
Spring	3.4	0.9	0.2	1.0	0.1	1.1	5.3
Summer	4.1	1.3	0.2	1.6	0.2	0.9	6.4
Autumn	3.2	1.2	0.1	1.2	0.2	0.5	3.7
ANNUAL	3.4	1.1	0.2	1.2	0.2	0.7	4.7

Season	Fine Mass	Sulfate	Nitrate	Organics	Elemental Carbon	Soil	Coarse Mass
CENTRAL ROCKIES							
Winter	2.0	0.5	0.2	0.9	0.1	0.3	3.0
Spring	3.4	0.9	0.3	1.1	0.1	1.1	4.3
Summer	4.8	1.0	0.1	2.4	0.2	0.9	7.5
Autumn	2.9	0.8	0.1	1.3	0.1	0.5	4.0
ANNUAL	3.3	0.8	0.1	1.3	0.1	0.5	4.0
CENTRAL COAST							
Winter	5.6	0.9	1.9	2.3	0.4	0.2	7.7
Spring	4.2	1.4	0.8	1.5	0.2	0.3	9.3
Summer	4.5	1.9	0.8	1.4	0.1	0.2	10.7
Autumn	5.7	1.4	1.0	2.7	0.4	0.3	7.8
ANNUAL	5.0	1.4	1.1	1.9	0.3	0.2	8.9
FLORIDA							
Winter	5.5	2.4	0.7	1.9	0.4	0.2	8.5
Spring	7.7	3.8	0.9	2.1	0.3	0.7	8.0
Summer	9.1	2.5	0.5	3.0	0.3	2.7	13.6
Autumn	6.9	3.1	0.5	2.3	0.4	0.5	8.6
ANNUAL	7.1	2.9	0.7	2.3	0.4	0.9	9.6
GREAT BASIN							
Winter	1.1	0.3	0.1	0.5	0.0	0.1	1.0
Spring	2.4	0.5	0.1	0.9	0.0	0.9	3.7
Summer	4.5	0.7	0.1	1.7	0.1	1.9	8.2
Autumn	3.1	0.6	0.1	1.4	0.1	1.0	5.1
ANNUAL	2.8	0.5	0.1	1.1	0.1	1.0	5.0
HAWAII							
Winter	4.0	2.8	0.1	0.9	0.1	0.1	3.0
Spring	3.6	2.5	0.1	0.8	0.1	0.2	7.4
Summer	1.6	0.9	0.1	0.5	0.0	0.1	10.3
Autumn	3.4	2.5	0.1	0.8	0.1	0.1	9.3
ANNUAL	3.2	2.2	0.1	0.7	0.1	0.1	8.2

Season	Fine Mass	Sulfate	Nitrate	Organics	Elemental Carbon	Soil	Coarse Mass
NORTHEAST							
Winter	6.6	3.3	0.8	1.8	0.5	0.2	3.1
Spring	6.1	3.6	0.4	1.5	0.3	0.3	4.1
Summer	8.6	4.5	0.3	3.0	0.4	0.3	6.7
Autumn	5.6	3.0	0.4	1.6	0.4	0.2	4.1
ANNUAL	6.7	3.6	0.5	2.0	0.4	0.2	4.5
NORTHERN GREAT PLAINS							
Winter	3.4	1.2	0.6	1.1	0.1	0.5	3.9
Spring	5.0	1.9	0.6	1.3	0.1	1.0	6.0
Summer	5.6	1.8	0.2	2.2	0.2	1.2	9.7
Autumn	4.0	1.2	0.2	1.5	0.1	1.0	5.8
ANNUAL	4.5	1.5	0.4	1.5	0.1	0.9	6.3
NORTHERN ROCKIES							
Winter	5.3	1.0	0.6	3.0	0.5	0.3	2.5
Spring	4.6	1.1	0.2	2.4	0.3	0.6	4.2
Summer	5.4	0.9	0.2	3.0	0.3	1.0	9.2
Autumn	6.7	0.9	0.3	4.3	0.6	0.6	5.7
ANNUAL	5.5	1.0	0.3	3.1	0.4	0.6	5.5
SOUTHERN CALIFORNIA							
Winter	4.6	0.5	2.2	1.2	0.2	0.4	4.2
Spring	13.6	1.7	6.9	3.2	0.6	1.2	9.8
Summer	13.8	2.4	4.6	4.2	0.8	1.8	15.2
Autumn	8.1	1.1	3.1	2.0	0.4	1.5	13.2
ANNUAL	9.8	1.4	4.2	2.5	0.5	1.2	10.4
SONORA							
Winter	3.2	1.2	0.3	1.1	0.2	0.4	3.3
Spring	4.4	1.2	0.3	1.3	0.1	1.5	7.5
Summer	5.6	2.1	0.2	1.8	0.2	1.2	7.6
Autumn	4.5	1.7	0.2	1.7	0.2	0.8	5.8
ANNUAL	4.4	1.5	0.3	1.5	0.2	0.9	6.0

Season	Fine Mass	Sulfate	Nitrate	Organics	Elemental Carbon	Soil	Coarse Mass
SIERRA							
Winter	2.5	0.4	0.7	1.1	0.1	0.2	2.1
Spring	4.3	1.0	0.6	1.7	0.2	0.8	4.8
Summer	7.2	1.7	0.6	3.6	0.5	0.9	7.0
Autumn	4.4	0.9	0.6	2.1	0.3	0.5	5.3
ANNUAL	4.5	1.0	0.6	2.1	0.3	0.6	4.7
SIERRA/HUMBOLDT							
Winter	1.7	0.2	0.1	1.0	0.1	0.3	2.9
Spring	3.0	0.6	0.2	1.4	0.1	0.6	2.9
Summer	4.0	0.7	0.2	2.2	0.3	0.6	5.6
Autumn	2.8	0.4	0.1	1.7	0.2	0.4	2.7
ANNUAL	2.9	0.5	0.2	1.6	0.2	0.5	3.7
WASHINGTON, DC							
Winter	16.3	5.4	3.4	4.9	2.0	0.6	30.1
Spring	16.8	7.3	2.6	4.2	1.7	1.0	10.2
Summer	16.7	8.6	1.2	4.4	1.6	0.9	13.5
Autumn	15.3	6.6	1.6	4.4	2.0	0.8	8.4
ANNUAL	16.2	6.9	2.2	4.5	1.8	0.8	16.4
WEST TEXAS							
Winter	3.6	1.5	0.2	1.1	0.1	0.6	5.1
Spring	6.4	2.2	0.3	1.7	0.2	2.1	10.4
Summer	6.6	2.5	0.3	1.7	0.1	1.9	7.4
Autumn	4.8	2.3	0.2	1.4	0.2	0.8	7.0
ANNUAL	5.4	2.1	0.3	1.5	0.1	1.4	7.5

Appendix C

Seasonal and annual averages, averaged over the three-year period from March 1988 through February 1991, of percentage contributions to the reconstructed aerosol light extinction coefficient (light extinction budget) for the 19 regions in the IMPROVE network for sulfate, nitrate, organic carbon, light absorbing carbon, and coarse particles/fine soil. (Sisler, Huffman and Latimer, 1993).

Season	Sulfate	Nitrate	Organics	Elemental carbon	Soil and Coarse
ALASKA					
Winter	49.7	7.3	20.4	3.9	18.7
Spring	53.3	4.1	22.0	3.2	17.3
Summer	30.0	1.8	44.0	4.6	19.6
Autumn	41.5	5.6	28.8	5.4	18.7
ANNUAL	43.3	4.4	29.8	4.1	18.4
APPALACHIAN					
Winter	53.8	15.1	19.6	7.6	3.9
Spring	66.1	9.2	15.6	5.3	3.8
Summer	75.6	2.3	15.3	2.6	4.2
Autumn	68.6	5.8	16.7	5.1	3.8
ANNUAL	68.3	6.7	16.3	4.5	4.2
BOUNDARY WATERS					
Winter	46.2	33.0	14.1	3.2	3.4
Spring	60.9	8.6	20.2	3.6	6.6
Summer	50.4	2.9	33.9	4.2	8.6
Autumn	51.4	13.6	23.3	4	7.6
ANNUAL	51.1	14.5	24.2	3.7	6.5
CASCADES					
Winter	27.1	6.6	50.4	11.3	4.6
Spring	39.5	6.9	38.6	10.1	4.9
Summer	47.2	8.0	30.1	9.4	5.3
Autumn	38.4	5.7	39.6	10.9	5.4
ANNUAL	39.0	6.8	39.4	10.0	4.8
COLORADO PLATEAU					
Winter	37.7	14.8	25.5	9.5	12.4
Spring	31.5	7.9	25.1	6.0	29.5
Summer	32.3	4.4	29.9	8.9	24.4
Autumn	39.1	5.0	28.9	9.8	17.3
ANNUAL	35.3	7.0	27.6	8.6	20.5

Season	Sulfate	Nitrate	Organics	Elemental Carbon	Soil and Coarse
CENTRAL ROCKIES					
Winter	33.8	13.1	31.0	6.0	16.1
Spring	38.2	10.6	26.6	4.2	20.4
Summer	28.5	3.8	37.4	8.9	21.3
Autumn	35.3	5.6	33.8	7.6	17.7
ANNUAL	32.7	7.3	33.6	7.1	19.3
CENTRAL COAST					
Winter	21.5	35.6	26.9	6.8	9.3
Spring	37.4	20.9	21.7	4.9	15.1
Summer	44.2	17.2	18.2	4.0	16.4
Autumn	30.0	19.7	30.3	9.3	10.7
ANNUAL	33.0	24.0	24.5	6.2	12.2
FLORIDA					
Winter	53.0	15.5	17.7	5.4	7.5
Spring	59.0	13.6	16.6	3.7	7.1
Summer	44.9	9.7	26.5	4.2	14.6
Autumn	59.4	10.1	18.2	5.3	7.0
ANNUAL	54.6	12.2	19.8	4.6	8.6
GREAT BASIN					
Winter	38.8	18.5	32.3	1.8	8.7
Spring	31.3	8.4	31.4	2.4	26.6
Summer	16.9	2.8	34.8	5.7	39.7
Autumn	24.4	6.4	35.9	5.7	27.7
ANNUAL	25.3	6.5	34.1	4.1	29.9
HAWAII					
Winter	81.5	1.8	11.2	1.8	3.6
Spring	74.4	2.5	11.6	1.4	10.1
Summer	52.8	5.0	13.7	1.8	26.8
Autumn	74.5	1.6	9.9	1.5	12.5
ANNUAL	72.8	2.4	11.6	1.6	11.7

Season	Sulfate	Nitrate	Organics	Elemental Carbon	Soil and Coarse
NORTHEAST					
Winter	58.8	13.3	16.7	7.8	3.4
Spring	65.0	7.9	14.9	6.6	5.6
Summer	62.7	4.8	21.5	5.4	5.5
Autumn	63.3	8.4	17.2	6.4	4.7
ANNUAL	62.4	8.4	17.9	6.5	4.8
NORTHERN GREAT PLAINS					
Winter	43.5	21.0	20.8	4.5	10.2
Spring	49.6	15.2	18.8	3.4	13.1
Summer	39.4	3.5	29.4	5.6	22.1
Autumn	39.9	6.9	28.4	6.1	18.7
ANNUAL	44.0	11.0	24.5	4.8	15.8
NORTHERN ROCKIES					
Winter	28.8	16.3	41.5	9.9	3.5
Spring	36.3	8.1	39.4	8.1	8.1
Summer	25.4	4.7	42.7	9.2	18.0
Autumn	21.9	7.4	52.3	11.2	7.2
ANNUAL	28.0	9.0	44.3	9.8	8.9
SOUTHERN CALIFORNIA					
Winter	12.0	50.6	17.8	8.8	10.8
Spring	13.3	55.7	15.7	6.8	8.4
Summer	16.8	32.5	22.3	11.8	16.5
Autumn	12.7	36.7	17.3	10.1	23.2
ANNUAL	14.4	44.4	18.2	9.0	13.9
SONORA					
Winter	44.6	9.7	24.4	8.8	12.5
Spring	28.0	7.3	25	7.0	32.8
Summer	40.8	4.0	25.7	7.0	22.5
Autumn	34.4	3.8	27.8	10.8	19.2
ANNUAL	38.8	5.9	25.7	8.4	21.1

Season	Sulfate	Nitrate	Organics	Elemental Carbon	Soil and Coarse
SIERRA					
Winter	16.9	30.9	34.1	7.5	10.6
Spring	31.7	18.8	29.3	6.5	13.8
Summer	22.1	7.6	38.1	15.6	16.6
Autumn	21.0	13.4	35.6	13.0	16.9
ANNUAL	24.5	15.3	34.8	10.8	14.6
SIERRA/HUMBOLDT					
Winter	22.1	11.1	42.3	9.0	15.5
Spring	28.6	12.2	39.7	7.3	12.2
Summer	22.7	5.7	42.0	11.8	17.8
Autumn	22.1	4.9	46.9	13.1	13.0
ANNUAL	24.4	7.9	42.8	10.1	14.9
WASHINGTON, DC					
Winter	34.9	22.0	16.9	13.6	12.6
Spring	50.0	17.7	15.2	12.0	5.0
Summer	62.0	8.9	15.2	8.9	4.9
Autumn	52.7	12.8	17.4	13.3	3.9
ANNUAL	49.0	16.0	16.2	11.9	6.9
WEST TEXAS					
Winter	44.2	6.8	22.7	7.0	19.3
Spring	36.6	5.1	21.6	5.8	30.9
Summer	49.0	6.0	21.1	4.1	19.8
Autumn	51.3	3.8	20.5	6.1	18.3
ANNUAL	45.5	5.4	21.4	5.6	22.2

Appendix D

Visibility Related Conferences				
Title	Date	Location	Sponsors	Reference
Plumes and Visibility: Measurements and Model Components	Nov. 1980	Grand Canyon National Park, AR, USA	EPA/NPS	Atmospheric Environment, Vol. 15, 1981
Visibility Protection: Research and Policy Aspects	Sept. 1986	Grand Teton National Park, WY, USA	AWMA	Transactions, AWMA
Visibility and Fine Particles	Oct. 1989	Estes Park, CO, USA	AWMA/EPA	Transactions, AWMA
Visibility and Fine Particles	Sept. 1992	Vienna, Austria	Institute of Experimental Physics	Atmospheric Environment, Vol. 28, 1994
Aerosols and Atmospheric Optics Radiation Balance and Visual Air Quality	Sept. 1994	Snow Bird, VT, USA	AWMA/AGU	Transactions will be published in specialty issues of journals