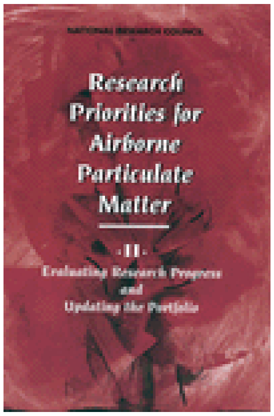

Research Priorities for Airborne Particulate Matter: II. Evaluating Research Progress and Updating the Portfolio

Committee on Research Priorities for Airborne Particulate Matter, National Research Council

ISBN: 0-309-59370-0, 128 pages, 6 x 9, (1999)

Research Priorities for Airborne Particulate Matter

• II •

Evaluating Research Progress and Updating the Portfolio

Board on Environmental Studies and Toxicology
Commission on Life Sciences
Commission on Geosciences, Environment, and Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.

NATIONAL ACADEMY PRESS 2101 Constitution Ave., N.W. Washington, D.C. 20418

This project was supported by Contract No. 68-C-98-003 between the National Academy of Sciences and U.S. Environmental Protection Agency. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for this project.

Library of Congress Catalog Card Number 99-66283

International Standard Book Number 0-309-06638-7

Additional copies of this report are available from: National Academy Press 2101 Constitution Ave., NW Box 285 Washington, DC 20055 800-624-6242 202-334-3313 (in the Washington metropolitan area) http://www.nap.edu

Printed in the United States of America

COMMITTEE ON RESEARCH PRIORITIES FOR AIRBORNE PARTICULATE MATTER

JONATHAN SAMET (*Chair*), Johns Hopkins University, Baltimore, Maryland
GLEN CASS, California Institute of Technology, Pasadena, California
JUDITH CHOW, Desert Research Institute, Reno, Nevada
BART E. CROES, California Air Resources Board, Sacramento, California
ROBERT E. FORSTER, The University of Pennsylvania School of Medicine, Philadelphia, Pennsylvania
DANIEL S. GREENBAUM, Health Effects Institute, Cambridge, Massachusetts
MAUREEN HENDERSON, University of Washington, Seattle, Washington
PHILIP K. HOPKE, Clarkson University, Potsdam, New York
PETROS KOUTRAKIS, Harvard University, Boston, Massachusetts
DANIEL KREWSKI, University of Ottawa, Ottawa, Ontario
PAUL LIOY, University of Medicine and Dentistry-New Jersey, Piscataway, New Jersey
JOE L. MAUDERLY, Lovelace Respiratory Research Institute, Albuquerque, New Mexico
ROGER O. MCCLELLAN, Chemical Industry Institute of Toxicology, Research Triangle Park, North Carolina
GÜNTER OBERDÖRSTER, University of Rochester, Rochester, New York
REBECCA PARKIN, George Washington University, Washington, D.C.
JOYCE E. PENNER, University of Michigan, Ann Arbor, Michigan
RICHARD SCHLESINGER, New York University School of Medicine, Tuxedo, New York
FRANK E. SPEIZER, Harvard Medical School, Boston, Massachusetts
MARK UTELL, University of Rochester, Rochester, New York
RONALD WHITE, American Lung Association, Washington, D.C.
WARREN WHITE, Washington University, St. Louis, Missouri
RONALD WYZGA, Electric Power Research Institute, Palo Alto, California
TERRY F. YOSIE, Chemical Manufacturers Association, Arlington, Virginia

Project Staff

JAMES J. REISA, Principal Staff Officer
KULBIR BAKSHI, Senior Staff Officer
RAYMOND A. WASSEL, Senior Staff Officer
EILEEN ABT, Research Associate
JAMIE YOUNG, Research Associate
LEE PAULSON, Editor
MILLICENT ANDERSON, Assistant to the Director
TRACIE HOLBY, Senior Project Assistant

BOARD ON ENVIRONMENTAL STUDIES AND TOXICOLOGY

Senior Staff

COMMISSION ON LIFE SCIENCES

Staff

COMMISSION ON GEOSCIENCES, ENVIRONMENT, AND RESOURCES

OTHER REPORTS OF THE BOARD ON ENVIRONMENTAL STUDIES AND TOXICOLOGY

Ozone-Forming Potential of Reformulated Gasoline (1999)
Risk-Based Waste Classification in California (1999)
Arsenic in Drinking Water (1999)
Research Priorities for Airbome Particulate Matter: I. Immediate Priorities and a Long-Range Research Portfolio (1998)
Brucellosis in the Greater Yellowstone Area (1998)
The National Research Council's Committee on Toxicology: The First 50 Years (1997)
Toxicologic Assessment of the Army's Zinc Cadmium Sulfide Dispersion Tests (1997)
Carcinogens and Anticarcinogens in the Human Diet (1996)
Upstream: Salmon and Society in the Pacific Northwest (1996)
Science and the Endangered Species Act (1995)
Wetlands: Characteristics and Boundaries (1995)
Biologic Markers (5 reports, 1989–1995)
Review of EPA's Environmental Monitoring and Assessment Program (3 reports, 1994–1995)
Science and Judgment in Risk Assessment (1994)
Ranking Hazardous Waste Sites for Remedial Action (1994)
Pesticides in the Diets of Infants and Children (1993)
Issues in Risk Assessment (1993)
Setting Priorities for Land Conservation (1993)
Protecting Visibility in National Parks and Wilderness Areas (1993)
Dolphins and the Tuna Industry (1992)
Hazardous Materials on the Public Lands (1992)
Science and the National Parks (1992)
Animals as Sentinels of Environmental Health Hazards (1991)
Assessment of the U.S. Outer Continental Shelf Environmental Studies Program, Volumes I–IV (1991–1993)
Human Exposure Assessment for Airborne Pollutants (1991)
Monitoring Human Tissues for Toxic Substances (1991)
Rethinking the Ozone Problem in Urban and Regional Air Pollution (1991)
Decline of the Sea Turtles (1990)

Copies of these reports may be ordered from the National Academy Press (800) 624-6242 or (202) 334-3313
www.nap.edu

THE NATIONAL ACADEMIES

National Academy of Sciences
National Academy of Engineering
Institute of Medicine
National Research Council

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institutedicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

PREFACE

A major research effort is under way to improve scientific understanding of airborne particulate matter and its effects on human health. Requested and funded by Congress, and conducted by the U.S. Environmental Protection Agency (EPA), other federal and state government agencies, and nongovernmental organizations, this research effort is directed at reducing the scientific and technical uncertainties in the evidence related to regulation of airborne particulate matter in the United States.

At the request of Congress and EPA, the National Research Council's Committee on Research Priorities for Airborne Particulate Matter is independently advising and monitoring the implementation of the research. The committee's first report, *Research Priorities for Airborne Particulate Matter: I. Immediate Priorities and a Long-Range Research Portfolio,* was released in March 1998. It identified 10 high-priority research topics linked to key policy-related scientific uncertainties and presented a 13-year "research investment portfolio" containing recommended short-term and long-term timing, phasing, and estimated costs of research on each topic. The committee is pleased to note that Congress, EPA, and the scientific community have given strong support to the committee's recommendations and have implemented substantial changes in research efforts in response to the first report.

This is the second of four planned reports by the committee. In this report, the committee describes its plans for monitoring the progress of research. In addition, the research recommendations from the com mittee's first report are reviewed and updated, and two of the recommended research areas are substantially revised. Subsequent reports in 2000 and 2002 will describe and evaluate the results of the research.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report: Arthur DuBois, Yale University; Sheldon Friedlander, University of California at Los Angeles; Robert Frosch, Harvard University; Carol Henry, Chemical Manufacturers Association; Donald Hornig (review monitor), Harvard University; Morton Lippmann, New York University; Donald Mattison (review coordinator), March of Dimes Birth Defects Foundation; Thomas Peterson, University of Arizona; and Robert Phalen, University of California at Irvine.

While the individuals listed above have provided many constructive comments and suggestions, it must be emphasized that responsibility for the final content of this report rests entirely with the authoring committee and the NRC.

The committee gratefully acknowledges John Bachmann, Daniel Costa, Robert Devlin, William Farland, Judith Graham, Lester Grant, Henry Longest, Peter Preuss, Frank Princiotta, Kenneth Reid, Lawrence Reiter, Richard Scheffe, John Vandenberg, and James Vickery of the U.S. Environmental Protection Agency; George Malindzak of the National Institute for Environmental Health Sciences; Daniel Albritton of the National Oceanic and Atmospheric Administration; Doyle Pendleton of Southwest Texas State University; Charles Pietarinen of the New Jersey Department of Environmental Protection; Melvin Zeldin of the South Coast Air Quality Management District; and Steven Cadle of General Motors (representing NARSTO, a multinational North American consortium for atmospheric research in support of air-quality management) for making presentations or providing information to the committee.

In addition, we are grateful to the 40 or so EPA and EPA-supported scientists who made research poster presentations to the committee on June 23, 1998, in Research Triangle Park, NC.

We are grateful for the assistance of the NRC staff in preparing the report. Staff members who contributed to this effort are James J. Reisa, director of the Board on Environmental Studies and Toxicology and principal staff officer for the committee; Raymond Wassel and Kulbir Bakshi, senior staff officers; Laurie Geller, staff officer; Eileen Abt and Jamie Young, research associates; Lee Paulson, editor; Millicent Anderson, assistant to the director; and Tracie Holby, senior program assistant.

Finally, I would like to thank all the members of the committee for their dedicated efforts throughout the development of this report.

JONATHAN SAMET, M.D., M.S.

CHAIR, COMMITTEE ON RESEARCH PRIORITIES FOR AIRBORNE PARTICULATE MATTER

CONTENTS

TABLES

FIGURES

Research Priorities for Airborne Particulate Matter:

II. EVALUATING RESEARCH PROGRESS AND UPDATING THE PORTFOLIO

EXECUTIVE SUMMARY

This is the second in a series of reports by the Committee on Research Priorities for Airborne Particulate Matter. The committee was convened by the National Research Council (NRC) in January 1998 at the request of the U.S. Environmental Protection Agency (EPA) pursuant to directions from Congress in EPA's Fiscal Year 1998 appropriations report. The congressional request for this study arose from the scientific uncertainties in the evidence base for EPA's July 1997 decision to establish new National Ambient Air Quality Standards (NAAQS) for particulate matter (PM). Anticipating the next scheduled review of the standards in 2002 and every 5 years thereafter, Congress directed, and provided substantial funds for, a major research program to reduce the scientific uncertainties, and it directed EPA to arrange for this independent NRC study to develop guidance for planning the research program and to monitor research progress for the 5 years of 1998–2002.

THE COMMITTEE'S 1998 REPORT

The committee's first report, *Research Priorities for Airborne Particulate Matter: I. Immediate Priorities and a Long-Range Research Portfolio* , was released in March 1998. It proposed a conceptual framework for a national program of PM research; identified ten high-priority research topics linked to key policy-related scientific uncertainties; and presented a 13-year, integrated "research investment portfolio" containing recommended short-and long-term timing, phasing, and estimated costs of such research. In developing its research recommendations, the committee did not undertake to evaluate the adequacy of the scientific foundation for EPA's 1997 decision to establish new PM standards, recognizing that such a decision must involve policy judgments beyond the realm of science that the committee was neither charged nor constituted to make.

RESPONSE TO THE 1998 REPORT

In response to the committee's first report, Congress and EPA made substantial changes in EPA's research program and other technical activities related to particulate matter. Congress quickly gave strong support to the committee's recommendations in EPA's Fiscal Year 1999 appropriations report and provided $47.3 million for EPA's PM research in 1999, an increase of $25.4 million over President Clinton's 1999 budget request. An additional $8.3 million was provided to EPA's research program for related technical work in 1999. The President's request for Fiscal Year 2000 tracks the committee's recommendations closely, designating a total of $51.6 million for PM research and an additional $10.3 million for related technical work. Through in-house studies at EPA laboratories and centers, EPA funding of university-based research centers and investigator-initiated competitive research grants, and enhanced collaboration with other agencies and organizations, the overall research effort on particulate matter has been substantially increased. For example, in terms of overall resources, Congress increased the budget for research on quantitative relationships between outdoor concentrations of particulate matter and actual human exposures (recommended as Research Topic 1 in the committee's 1998 report) from $3.6 million in the President's proposed budget for Fiscal Year 1999 to $8.2 million in the 1999 appropriations, and EPA has proposed $7.9 million for Fiscal Year 2000. The committee also considers it noteworthy that EPA's National Exposure Research Laboratory has increased its in-house activities and scientific expertise in this research area. In the area of research to identify the biologically active constituents and toxicity-determining characteristics of particulate matter that produce adverse health effects (Research Topic 5 in the committee's 1998 report), EPA resources were increased from $4.5 million in the President's proposed budget for Fiscal Year 1999 to $7.9 million in the 1999 appropriations, and EPA has proposed $6.7 million for Fiscal Year 2000. In the important area of research to better understand the relationships between particulate matter and other pollutant exposures and their effects on health (Research Topic 7 in the committee's 1998 report), the EPA level of effort was increased from $0.8 million in the President's proposed 1999 budget to $7.4 million in the 1999 appropriations, and EPA has proposed $8.5 million for Fiscal Year 2000. Resources for investigating the underlying toxicological mechanisms to explain epidemiological findings of adverse health outcomes associated with PM exposures (Research Topic 9 in the committee's 1998 report) were increased from $4.3 million in the President's proposed 1999 budget to $8.3 million in the 1999 appropriations, and EPA has requested $6.8 million for this area of research in Fiscal Year 2000.

Although most of the research activities recommended in the committee's first report are now being addressed or planned by EPA or other organizations, the committee identified one cross-cutting research area of critical importance that does not yet appear to be adequately under way or planned—studies of the effects of *long-term* exposure to particulate matter and other major air pollutants. This area of research is very important to several of the research categories (Research Topics 5, 7, and 8) recommended in the committee's first report. There is an overarching need for federal research programs, in collaboration with other research organizations, to begin actively planning and implementing such research.

One of the concerns expressed in the committee's first report was the lack of strong interactions with the scientific community in EPA's planning for major monitoring programs to measure PM mass and airborne particle composition on a routine basis. The committee also expressed concern about insufficient detailed compositional and time-resolved measurements. In response to that report and because of other considerations, EPA improved coordination among the three parts of the monitoring program and is working with the scientific community to enhance the potential research value of the monitoring data while fulfilling the agency's need to determine attainment of the

PM standards and to provide information for the development of implementation plans for areas that might be found to be in a nonattainment status for the PM standards. EPA has more than doubled the number of planned continuous $PM_{2.5}$ monitoring sites from 50 to more than 100 nationwide, revised plans for the routine chemical-speciation monitoring program to include ten trend sites where PM chemical-speciation measurements will be made every day, and extended some deadlines for the supersites program to allow better coordination with health-effects field studies.

The committee supports these changes in EPA's PM research and ambient monitoring programs, and it applauds the actions taken by EPA and Congress. The committee expects these programs to have the potential to produce findings that will improve the basis for regulatory decisionmaking on particulate matter and scientific knowledge of air pollution generally.

EPA's Clean Air Scientific Advisory Committee (CASAC) created a technical subcommittee on PM monitoring that is chaired by a member of this NRC committee and has two additional NRC committee members serving on it. CASAC is also chaired by a member of this NRC committee. The overlapping membership is expected to ensure that CASAC and this committee will be well coordinated in providing scientific advice for EPA's PM monitoring programs.

EVALUATING THE IMPLEMENTATION AND PROGRESS OF PARTICULATE-MATTER RESEARCH

In this report, the committee discusses its plans and related considerations for monitoring and evaluating the progress of research on particulate matter[1] (Chapter 2). Then, taking recent developments and new information into account, it updates the research topics and portfolio presented in its 1998 report (Chapter 3). This report does not attempt to assess the results of research conducted in response to the commit

[1] Some researchers use the term "atmospheric aerosol" or "ambient aerosol" to refer to airborne particulate matter. An aerosol is a suspension of solid or liquid particles in a gas.

tee's first report, which was published last year. It is too soon for such an assessment. The committee's next two reports in 2000 and 2002 will review this research.

The committee's first report identified the following three principal criteria for identifying research priorities for particulate matter:

1. ***Scientific Value***—How well does the research fill important data gaps, provide information on causal relationships, build on previous findings, and contribute to the development of an integrated understanding of the health effects of particulate matter and gaseous copollutants?
2. ***Decisionmaking Value***—How well does the research contribute to reducing key uncertainties associated with regulatory standard-setting and risk-management decisions?
3. ***Feasibility and Timing***—Is the research technically, operationally, and financially feasible, and is it conducted on a time frame responsive to decisionmakers' needs?

The committee concludes that the above criteria will also serve well in evaluating the progress and results of the research, and it plans to apply them for that purpose.

The committee now introduces three additional criteria that pertain to evaluating the planning, management, and implementation of the research:

4. ***Interaction***—How well do the scientists involved in the research engage in collaboration across scientific disciplines, and how well are the scientific capacity and resources leveraged to enhance productivity?
5. ***Integration***—How well is research planning, management, and budgeting integrated in a joint process involving governmental and private organizations?

6. ***Accessibility***—How effectively is information conveyed and shared among research organizations and others concerning research planning, budgeting, progress, and results?

The committee intends to apply these additional criteria in its evaluation of PM research programs. The additional criteria recognize the need for PM research to be a national effort involving not only EPA, but many other agencies and research organizations that must communicate and collaborate effectively across many scientific disciplines.

Historically, despite efforts by EPA, the interagency Committee on Environment and Natural Resources, NARSTO (a multinational, public-private consortium for atmospheric research in support of air-quality management), and others, the goals of multi organizational integration and multidisciplinary interaction have been as elusive for PM research as they have been for many other areas of research. The various research organizations and disciplines often have different interests, technical approaches, funding sources, and professional cultures. Too often, the only attempts at interaction and integration have been described as informal or ad hoc, and they often have not been very effective.

In Chapter 2 of this report, the committee recommends that the government develop a coordinated interagency strategy that includes:

1. A process and interagency budget to plan and implement the PM research portfolio recommended by the committee.
2. The mechanisms that will be used to coordinate research across agencies on a continuing basis.
3. Strategies and mechanisms for leveraging federal funding with state governments, private industry, and nonprofit organizations.

The committee also recommends that EPA develop a formal research-integration plan and a coordinated planning process that includes the following components for each of the committee's recommended research topics:

1. Objectives, timeframes, and estimated costs.
2. Required scientific and technical disciplines and skills.
3. Plans and rationales for deciding which research activities should be conducted intramurally or extramurally, and which research should be leveraged through multiorganizational funding.
4. Ongoing efforts (e.g., internet and newsletters) to communicate research progress to the scientific community and the public.

The committee also believes there is an urgent need for an on-line-accessible inventory of PM research activities—a database that summarizes the research and links each activity to the committee's research portfolio categories. The committee has developed a prototype database for such an inventory, but further development and maintenance of the database should be undertaken by EPA, perhaps in partnership with the Health Effects Institute, which, with EPA, has already prepared summaries of research in progress.

As part of the research-planning process, the committee recommends that EPA periodically compare its research plans and activities with the committee's research portfolio and the committee's six criteria for evaluating research. Over the next four years, in preparation for its third and fourth reports in 2000 and 2002, the committee will array the results of PM research sponsored by EPA and other organizations against the committee's recommended research portfolio in an ongoing assessment of research progress and of the remaining gaps that need to be addressed. The committee will compare research implementation and results with the criteria stated above. Particular emphasis will be placed on evaluating the value of research results in reducing the scientific uncertainties faced by public decisionmakers in setting and implementing standards. The committee will conduct a series of public workshops to evaluate the progress of EPA's PM research program and to compare its progress with that of other agencies and research organizations. Such workshops will involve research scientists, research managers, and policymakers from EPA, other federal and state agencies, universities, and the private sector, including industry and nonprofit organizations.

UPDATING THE COMMITTEE'S PORTFOLIO OF RECOMMENDED RESEARCH

The portfolio of recommended research topics initially presented in the committee's 1998 report is intended to be updated and revised as research results are obtained and as changing circumstances warrant. In Chapter 3 of this report, the committee reviews and updates eight of the ten high-priority research topics recommended in its first report, and it revises and renames two of the topics (i.e., research topics 3 and 4), as summarized below.

1. *Outdoor Measures versus Actual Human Exposures*. As discussed in the committee's 1998 report, this is an important area of research involving field studies and longitudinal panel studies of the quantitative relationships between concentrations of particulate matter (and gaseous copollutants) measured at stationary outdoor air-monitoring sites and the actual breathing-zone exposures of individuals to the pollutants, taking into account ambient outdoor and indoor pollutant sources and human time-activity patterns. This is particularly important for potentially susceptible subpopulations.

Update: In a substantial and commendable response to the committee's first report, EPA's Office of Research and Development initiated a human exposure-assessment research plan for particulate matter that dramatically increases and improves the agency's intramural and extra-mural research efforts in this area. In terms of overall resources, Congress increased the budget for this category of research from $3.6 million in the President's proposed budget for Fiscal Year 1999 to $8.2 million in the 1999 appropriations, and EPA has proposed $7.9 million for Fiscal Year 2000. The committee also considers it noteworthy that EPA's National Exposure Research Laboratory is increasing its in-house scientific activities and expertise in this research area. EPA laboratory scientists will characterize microenvironmental PM exposures, human exposures to ultrafine particles, and processes governing the penetration of outdoor particles into indoor environments. EPA is also funding university research on exposure and dose modeling, as well as characterization of exposures of sensitive subpopulations to particulate matter and related gaseous copollutants in several urban areas. In addition, EPA has taken steps to improve coordination of its exposure-research activities with other organizations, as well as with EPA's PM monitoring program.

2. *Exposures of Susceptible Subpopulations to Toxic PM Components*. As recommended in the committee's first report, this area of research will investigate exposures to the most biologically relevant constituents and characteristics of particulate matter that might adversely affect health, especially for potentially susceptible subpopulations.

Update: Most of the research activities included in this topic are not expected to begin until necessary information from toxicological studies becomes available. However, it would be beneficial to start immediately some small-scale efforts to develop new tools and information for the subsequent exposure-research projects. Studies should begin soon on the intercomparison of personal samplers, temporal-variability of personal exposures, exposure misclassification, physicochemical properties of personal exposures, personal exposures to bioaerosols, and the development of individual and population exposure models.

3. *Characterization of Emissions Sources (Revised Topic)*. Based on new information about current and planned emission-characterization and model-development activities, the committee has reorganized and renamed Research Topic 3 to provide more explicitly for the acquisition of emissions data that will be needed to formulate emissions-management strategies. The revised focus is on the development of measurement methods to characterize the size-distribution, chemical composition, and emission rates of primary particles from sources throughout

the United States, as well as emission rates of reactive gases that lead to particle formation by atmospheric chemical reactions. Once developed and tested, these measurement methods will have to be applied to a large number of sources to collect the data needed to design successful management strategies. The committee regards these data-collection efforts as necessary technical support for regulatory programs. They can be performed by governmental regulatory or research programs at the federal or state level or by nongovernmental organizations. The required data include chemically speciated and size-resolved emissions data for a sufficient number of geographically representative situations and source types, compiled into a comprehensive emissions inventory that can be used by scientists and regulatory decisionmakers.

4. *Air-Quality Model Development and Testing (Revised Topic)*. Based on new information about current and planned model-development and ambient-monitoring activities, the committee has reorganized and renamed Research Topic 4 to provide more explicitly for research to develop, test, and evaluate source-oriented and receptor-oriented predictive models that represent the linkages between emission sources and ambient concentrations of the most biologically relevant components of particulate matter. Source-oriented models require an improved understanding of the chemical and physical processes that determine the size distribution and chemical composition of ambient particles. Receptor-oriented models require better mathematical tools for identifying patterns in the spatial and temporal variability of particle concentration and composition. To be used with confidence, receptor and source model results must be compared with each other and tested against observations from intensive field-measurement campaigns. Strong air-quality monitoring programs are essential foundations of such intensive campaigns, and the committee supports EPA's recent adjustments to make its planned monitoring of particulate matter more useful for model evaluation. These adjustments include an increase in the planned number of continuous ambient $PM._{2.5}$-monitoring sites from 50 to more than 100 and revised plans for the $PM_{2.5}$, chemical-speciation trend-monitoring programs to include ten sites where speciation will be done every day and 44 sites where it will be done every third day. The committee encourages EPA to maximize its

interactions with the atmospheric modeling, exposure, and health science communities as the monitoring supersites are developed. Such interactions in the past have not been sufficient.

5. *Hazardous PM Components*. The committee's first report urged that high priority be assigned to toxicological and epidemiological studies to identify the most biologically relevant constituents and characteristics of particulate matter that produce adverse health effects.

Update: In response to the committee's 1998 recommendation for increased work in this area of research, Congress increased the resources from $4.5 million in the President's proposed budget for fiscal 1999 to $7.9 million in the 1999 appropriations, and EPA has proposed $6.7 million for Fiscal Year 2000. EPA and other organizations are conducting or planning several toxicological studies in this area, including studies using concentrated air particles or surrogates and dose metrics for mass, number, and surface area of inhaled particles. An epidemiological study to examine the relationships between several size and chemical fractions of PM and several acute health end points is under way in Atlanta. Greater efforts will be needed to investigate the chronic toxicity of particle constituents.

6. *Dosimetry*. As discussed in the committee's first report, research is needed on the deposition patterns and fate of particles in the respiratory tract of individuals potentially susceptible to particulate matter, such as persons with chronic heart and lung disease.

Update: Research in this area has been initiated or planned by EPA, the Department of Energy, the Health Effects Institute, and others. In addition to the research previously recommended under this category in its first report, the committee recommends more investigation of PM dosimetry in different species of commonly-used laboratory animals to aid in the development of models for extrapolation to human dosimetry.

7. *Combined Effects of Particulate Matter and Other Pollutants*. The committee's first report identified this as a critical area of research,

because the air pollution that produces public-health effects is typically a complex mixture of pollutants. This research topic involves the investigation through toxicological and epidemiological studies of the combined effects or interactions between particulate matter and gaseous copollutant exposures in producing adverse health effects.

Update: In response to the committee's first report, which urged a substantial increase in this area of research, Congress increased the budget from $0.4 million in the President's proposed 1999 budget to $7.4 million in the 1999 appropriations, and EPA has proposed $8.5 million for Fiscal Year 2000. The committee supports these decisions. Studies have been funded by EPA and other organizations, including population-based studies of individual exposures to particulate matter and copollutants, controlled clinical studies, and studies of exposure biomarkers in human lung tissue.

8. *Susceptible Subpopulations*. As discussed in the committee's first report, research is needed to identify the human subpopulations that are potentially at greatest risk of adverse health effects from PM exposures (e.g., children, the elderly, and people with chronic respiratory diseases, cardiopulmonary diseases, or compromised immune systems).

Update: EPA and several other organizations are sponsoring studies of susceptibility factors, especially for pre-existing cardiopulmonary disease. Some laboratory-animal models of human disease have been developed, and others are being formulated. Controlled human-exposure studies using concentrated or surrogate particles are also being undertaken. It is difficult to assess all of these studies, because there is no central inventory of research projects dealing with susceptible subpopulations. It will be important for EPA to plan and implement its research activities in this area so as to build upon previous studies and to be well-coordinated and leveraged among federal and private research organizations. EPA's planning should take into account opportunities offered by such major studies as the Women's Health Initiative, the EPRI Veterans' Study, Harvard studies of medical personnel, inner-city asthma studies in various areas, and studies by large health-management organizations. The committee also recommends that EPA explore greater collaboration with other federal and nonfederal re search programs to leverage resources and maximize research opportunities.

9. *Mechanisms of Injury*. In its first report, the committee recommended that high priority be assigned to studies of the toxicological mechanisms by which particulate matter produces mortality and acute or chronic morbidity using laboratory-animal models, human clinical studies, and *in vitro* test systems.

Update: In response to the committee's first report, which recommended increased work in this area, Congress increased the research budget from $4.3 million in the President's proposed 1999 budget to $8.3 million in the 1999 appropriations, and EPA has requested $6.8 million for this area of research in Fiscal Year 2000. Many relevant clinical, animal, and *in vitro* studies are under way or planned. This topic now includes the development of advanced analytical methods for monitoring biological responses to toxic components of particulate matter, which was previously included under Research Topic 3 in the committee's first report.

10. *Analysis and Measurement*. In this category, the committee recommended the development and application of advanced methods for statistical analysis of epidemiological studies and for dealing with measurement and misclassification errors in estimating adverse health effects of particulate matter. Studies with detailed environmental data present methodological challenges that need to be addressed. In addition, as understanding of the biological relationships between pollution and health increases, models must incorporate this understanding.

Update: Research is under way to characterize the impacts of measurement error. Methods are also being developed to estimate the extent to which the timing of deaths may be advanced by exposures to pollutants.

COST IMPLICATIONS

In its first report, the committee judged EPA's proposed $21.9 million budget for PM research in Fiscal Year 1999 to be insufficient and rec ommended that it be substantially increased. The committee applauds the addition by Congress of $25.4 million to that budget, bringing EPA's Fiscal Year 1999 PM research budget to $47.3 million (plus an additional $8.3 million in related technical activities). The committee also endorses EPA's recently proposed PM research budget of $51.6 million (plus an additional $10.3 million for related technical work) for Fiscal Year 2000.

The committee has revised its cost estimates for some of the research areas recommended in its 1998 report, based on considerations discussed in Chapter 3 of this report and summarized above, as well as on the committee's evolving estimate of the extent to which PM monitoring programs will meet the critical data needs of certain research activities. The revised estimates increase the remaining 11-year (2000-2010) total cost of the committee's research portfolio from about $357 million to about $370 million, or from an annual average of $32.5 million to $33.6 million. It is necessary to recognize, however, that many parts of the research effort will continue to depend heavily upon data developed in supporting technical programs. Examples of such activities are testing of emissions sources, compilation of emission inventories, and much of the collection of ambient data to support testing and evaluation of air-quality models. These supporting technical activities may be conducted by government regulatory or research programs or by nongovernmental organizations.

RECENT DEVELOPMENTS

On May 14, 1999, a panel of the U.S. Court of Appeals for the District of Columbia Circuit remanded several NAAQS issued by EPA in July 1997, including the new standards for $PM_{2.5}$. The court required EPA to provide more explanation of its decisionmaking process and criteria in setting the standards. There is some uncertainty as to the potential impact, if any, of the court's decision on EPA's implementation schedule for PM NAAQS (Table 1.1). The committee holds a strong view that the PM research program should continue to move forward expeditiously. Whatever the resolution of legal proceedings, public-health and regulatory issues concerning particulate matter will remain. This is an area in which scientific uncertainties are of paramount importance to public policy, and a promising national research effort to reduce those uncertainties has been initiated at great effort and expense. A research program of this scope cannot be stopped and easily started again, and any significant disruption in the current and planned research efforts might be very costly to the nation in public-health and economic terms.

1

THE COMMITTEE'S FIRST REPORT AND ITS IMPACT

This is the second in a series of reports by the Committee on Research Priorities for Airborne Particulate Matter. The committee was convened by the National Research Council (NRC) in January 1998 at the request of the U.S. Environmental Protection Agency (EPA), pursuant to directions from Congress in EPA's Fiscal Year 1998 appropriations report. The committee's first report, *Research Priorities for Airborne Particulate Matter: I. Immediate Priorities and a Long-Range Research Portfolio* , was released in March 1998. To date, the committee has held five meetings: four at the National Academy of Sciences in Washington, D.C., and one at the EPA research facility in Research Triangle Park, North Carolina. At those meetings, the committee heard presentations from scientists and officials of EPA and other government agencies and nongovernmental organizations. The committee was charged to produce a total of four reports over 5 years, 1998–2002.

The congressional request for this independent NRC study arose from scientific uncertainties surrounding EPA's July 1997 decision to establish new National Ambient Air Quality Standards (NAAQS) for particulate matter (PM) smaller than 2.5 microns in aerodynamic diameter (EPA 1997). Contemplating the next and subsequent reviews of the new standards in 2002 and every 5 years thereafter, and EPA's proposed schedule for regulatory implementation of the new standards (Table 1.1), Congress mandated and provided substantial funds for EPA to conduct a major research program to reduce the scientific uncertainties, and it directed the EPA administrator to arrange for the NRC to

TABLE 1.1 EPA's Review and Implementation Timetable for Particulate-Matter Standards*

Past Actions	
1971	EPA issues TSP NAAQS
1979–1987	Review of criteria and standards
1987	EPA issues PM_{10} NAAQS
1994–1997	Review of criteria and standards
1997	EPA issues $PM_{2.5}$ and revised PM10 NAAQS
Planned Review and Implementation of $PM_{2.5}$ NAAQS	
1999	EPA will designate areas as "unclassifiable" regarding attainment of the NAAQS for $PM_{2.5}$
1998–2000	$PM_{2.5}$ monitors to be in place nationwide
1998–2003	$PM_{2.5}$ monitoring data to be collected nationwide
2002	EPA will complete 5-year scientific review of $PM_{2.5}$ standards, leading to possible revision
2002–2005	EPA will designate nonattainment areas for $PM_{2.5}$
2005–2008	States will submit implementation plans for meeting the $PM_{2.5}$ standard.
2012–2017	States will have up to 10 years to meet $PM_{2.5}$ standards plus two 1-year extensions

* The impact of the 5/14/99 U.S. appeals court decision on this timetable is not possible to predict at this time.

provide independent guidance for planning the research program and monitoring its implementation. Specifically, the committee was charged to assess research priorities, develop a conceptual research plan, and monitor research progress toward improved understanding of the relationships between airborne particulate matter, its various sources, and its effects on public health (the committee's formal statement of task is presented in Appendix B).

The committee's first report proposed an overall conceptual framework for an integrated national program of PM research (Figure 1.1). It identified ten high-priority research needs linked to key policy-related scientific uncertainties (Table 1.2), and it presented an integrated "research portfolio" containing recommended short-and long-term timing, phasing, and estimated resource requirements for such research (Table 1.3). The committee's first report did not undertake to evaluate the adequacy of the scientific foundation for EPA's 1997 decision to issue new PM standards, recognizing that such a decision involved policy judgments beyond the realm of science that the committee was neither charged nor constituted to make. Instead, the report identified uncertainties in the scientific information that should be addressed to strengthen the scientific foundation for future policy decisions.

In response to the committee's first report, Congress and EPA made substantial changes in EPA's research program and other technical activities related to particulate matter. Through in-house studies at EPA laboratories and centers, EPA funding of university-based research centers and investigator-initiated competitive research grants, and enhanced collaboration with other agencies and organizations, the overall research effort on particulate matter has been dramatically improved.

Table 1.4 summarizes changes made by Congress and EPA in the levels of resources devoted to the ten categories of research recommended by this committee. In response to the committee's first report, Congress quickly gave strong support to the committee's recommendations in EPAs' Fiscal Year 1999 appropriations report and provided $47.3 million for EPA's PM research in 1999, an increase of $25.4 million over President Clinton's 1999 budget request. An additional $8.3 million was provided to EPA's research program for related technical work in 1999. The President's request for Fiscal Year 2000 tracks the committee's recommendations closely, designating a total of $51.6 million for particulate-matter research and an additional $10.3 million

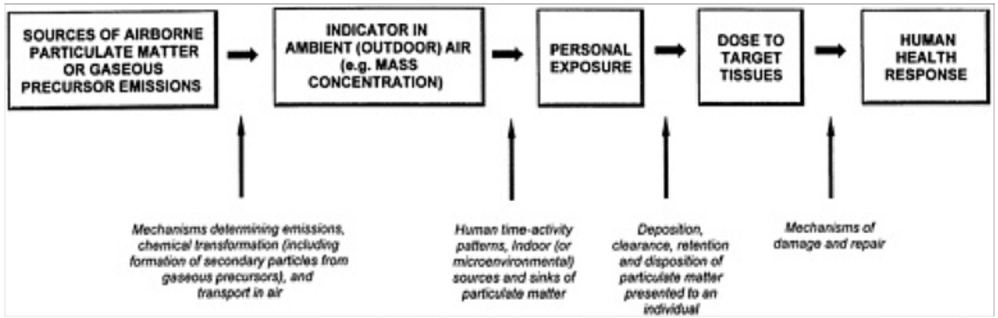

Figure 1.1 A general framework for integrating particulate-matter research. Source: Modified from NRC (1983, 1994), Lioy (1990), and Sexton et al. (1992).

TABLE 1.2 Key Scientific Uncertainties Related to the Source-to-Response Framework

Source → **Concentration (or other indicator)**

- Contribution of various emission sources to ambient and indoor particulate-matter concentrations
- Relative contribution of various sources to the most toxic components of particulate matter

Concentration (indicator) → **Exposure**

- Relationship between ambient (outdoor) particulate matter and the composition of particles to which individuals are exposed
- Contribution of ambient particulate matter to total personal exposure for:

Susceptible subpopulations
General population

- Variation in relationship of ambient particulate-matter concentrations to human exposure by place
- Variation in contribution of ambient particulate matter to total human exposure over time
- Covariance of particulate-matter exposures with exposures to other pollutants
- Relationship between outdoor ambient and personal exposures for particulate matter and copollutants

Exposure → **Dose**

- Relationship between inhaled concentration and dose of particulate matter and constituents at the tissue level in susceptible subjects

Asthma
Chronic Obstructive Pulmonary Disease (COPD)
Heart Disease
Age: infants and elderly
Others

Dose → **Response**

- Mechanisms linking morbidity and mortality to particulate-matter dose to or via the lungs

Inflammation
Host Defenses
Neural Mechanisms

TABLE 1.3 The Committee's Research Investment Portfolio: Timing and Estimated Costs* ($ million/year in 1998 dollars) of Recommended Research on Particulate Matter

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
SOURCE/CONCENTRATION/EXPOSURE													
1. Outdoor vs. human exposure	3.0	3.0	3.0										
2. Exposure to toxic PM components				4.0	4.0	4.0	4.0	4.0					
3. Source-receptor measurement tools													
3a. Atmospheric modeling	2.0	2.0	2.0	2.0	2.0	2.0							
3b. Receptor modeling	1.0	1.0	1.0										
3c. Analytical methods	1.0	1.0	1.0	1.5	1.5	1.5							
4. Application of methods and models	1.0	1.0	4.0	4.0	4.0	4.0	4.0	4.0					
EXPOSURE/DOSE-RESPONSE													
5. Assessment of hazardous PM components													
5a. Toxicological and clinical studies	8.0	8.0	8.0	8.0	8.0								
5b. Epidemiology		1.0	1.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
6. Dosimetry	3.0	1.5	1.5	1.5									
7. Effects of PM and copollutants													
7a. Copollutants (toxicology)	3.0	3.0	4.0	4.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
7b. Copollutants/long term (epidemiology)	1.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	3.0	3.0
8. Susceptible subpopulations	2.0	2.0	3.0	3.0	3.0	3.0	3.0	3.0					
9. Toxicity mechanisms													
9a. Animal models	3.0	3.0	3.0	3.0	3.0	3.0							
9b. *In vitro* studies	3.0	3.0	3.0	3.0	3.0	3.0							
9c. Human clinical	3.5	3.5	3.5	3.5	3.5	3.5							
ANALYSIS AND MEASUREMENT													
10a. Statistical analysis	0.5	1.0	1.0	1.0	1.0	1.0							
10b. Measurement error	1.0	1.5	1.5	1.5	0.5	0.5							
SUBTOTALS ($ MILLION PER YEAR)	36.0	41.5	46.5	52.0	49.5	41.5	28.0	28.0	17.0	17.0	17.0	14.0	14.0
RESEARCH MANAGEMENT** (ESTIMATED AT 10%)	3.6	4.2	4.7	5.2	5.0	4.2	2.8	2.8	1.7	1.7	1.7	1.4	1.4
TOTALS ($ MILLION PER YEAR)	39.6	45.7	51.2	57.2	54.5	45.7	30.8	30.8	18.7	18.7	18.7	15.4	15.4

*The committee's rough but informed collective-judgment cost estimates for the highest-priority research activities recommended in the committee's first report (NRC 1998). See Chapter 4 for explanations.

These estimates should *not* be interpreted as a recommended total particulate-matter research budget for EPA or the nation, for reasons explained in the report.

**Research management includes research planning, budgeting, oversight, review, and dissemination, cumulatively estimated by the committee at 10% of project costs.

TABLE 1.4 EPA Budgets for Particulate Matter Research

	EPA Appropriations ($ Million)				
	FY 1998 President's Budget	FY 1998 Enacted Appropriation	FY 1999 President's Budget	FY 1999 Enacted Appropriation	FY 2000 President's Budget
I. NRC Research Area					
1 Outdoor measures vs. actual human exposure	2.0	6.8	3.6	8.2	7.9
2 Exposure of susceptible subpopulations to PM components	0	0.5	0	0	1.0
3 Source-receptor measurement tools	4.1	5.9	4.4	7.0	5.9
4 Application of methods and models	0	0.7	0	0.4	2.7
5 Assessment of hazardous PM components	4.6	7.3	4.5	7.9	6.7
6 Dosimetry	0.5	1.2	0.5	0.6	0.9
7 Effects of PM and copollutants	0.4	1.9	0.8	7.4	8.5
8 Susceptible subpopulations	4.6	8.3	3.2	2.7	2.6
9 Mechanisms of injury	4.0	6.0	4.3	8.3	6.8
10 Analysis and measurement	0.5	1.7	0.6	1.2	1.4
Subtotal	20.7	40.3	21.9	43.7	44.4
Management	0	1.9	0	3.6	7.2
Total	20.7	42.0	21.9	47.3	51.6
II. Other Technical Activities					
Atmospheric chemistry, modeling, source apportionment	2.9	2.9	2.5	3.4	5.7
Emissions characterization, emission factors, controls	3.0	4.0	3.0	3.5	3.4
Criteria document development	1.3	1.3	1.3	1.4	1.2
Total	7.2	8.2	6.8	8.3	10.3
Combined Total	27.9	50.2	28.7	55.6	61.9

for related technical work. In general, the changes are highly responsive to the committee's recommendations. Examples of such changes are described for several research categories in Chapter 3.

Although most of the research activities recommended in the committee's first report are now being addressed by EPA or other organizations, the committee has identified one cross-cutting research area of critical importance that does not yet appear to be adequately under way or planned—studies of the effects of *long-term* exposure to particulate matter and other major air pollutants. This area of research is very important to several of the research categories (research topics 5, 7, and 8) recommended in the committee's first report. There is an overarching need for federal research programs, in collaboration with other research organizations, to begin actively planning and implementing such research.

In its first report, the committee expressed concern about the lack of strong interactions with the scientific community in EPA's planning for major monitoring programs to measure PM mass and airborne particle compositions on a routine basis, and the need for more detailed compositional and time-resolved measurements. In response to that report and because of other considerations, EPA made an effort to obtain input from a number of scientific groups and made a number of changes in its plans for the PM chemical speciation and supersites monitoring programs. EPA improved coordination among the three major parts of the monitoring program (i.e., mass-based, chemical speciation, and supersites) and is working with the scientific community to enhance the potential research value of the monitoring data while fulfilling the agency's need to determine attainment of the PM standards and to provide information for the development of implementation plans for areas that might be found to be in nonattainment of the PM standards.

EPA's Clean Air Scientific Advisory Committee (CASAC) created a technical subcommittee on PM monitoring, which is chaired by a member of this NRC committee. Two other NRC committee members serve on the subcommittee. CASAC also is chaired by a member of this NRC committee. The overlapping membership is expected to ensure that CASAC and this committee will be well coordinated in providing independent scientific advice for EPA's PM monitoring programs.

EPA increased the number of planned continuous $PM_{2.5}$ monitoring sites from 50 to more than 100 nationwide. The agency also revised plans for the routine chemical-speciation monitoring program to include ten trend sites where PM chemical-speciation measurements will be made every day and extended some deadlines for the supersites program to allow better coordination with health-effects studies. EPA acknowledged the potential to use the supersites for exposure and health-effects studies; however, EPA has not yet developed specific plans for such studies and has generally left their development to the research community. The committee encourages EPA to continue to pursue greater interactions with the atmospheric modeling and health-science communities in the definition and design of the supersites monitoring program.

The committee strongly supports the many changes made in EPA's PM research and monitoring programs, and it commends EPA and Congress for those actions.

On May 14, 1999, a panel of the U.S. Court of Appeals for the District of Columbia Circuit remanded several NAAQS issued by EPA in July 1997, including the new standards for $PM_{2.5}$ (EPA 1997). The court required EPA to provide more explanation of its decisionmaking process and criteria in setting the standards. There is some uncertainty about the potential impact, if any, of the court's decision on EPA's implementation schedule for PM NAAQS (Table 1.1).

The committee holds a strong view that the PM research program should continue to move forward expeditiously. Whatever the resolution of the legal proceedings, the public-health and regulatory issues concerning particulate matter will remain. This is an area in which scientific uncertainties are of paramount importance to public policy, and a promising national research effort to reduce those uncertainties has been initiated at great effort and expense. Once stopped, a research program of this scope could not easily be started again, and any significant disruption in the current and planned research efforts might be very costly to the nation in economic and public-health terms.

In the following pages, this report discusses the committee's approach for monitoring and evaluating the progress of the PM research program and, based on recent developments and new information, updates the research portfolio presented in the committee's 1998 re port. This report does not attempt to assess the results of research conducted in response to the committee's first report, which was published last year. It is too soon for such an assessment. The committee's next two reports in 2000 and 2002 will review this research.

2

EVALUATING RESEARCH IMPLEMENTATION AND PROGRESS

In this chapter, the committee discusses plans for monitoring and evaluating independently the progress of research on airborne particulate matter (PM),[1] responding to that element of its charge from Congress and the Environmental Protection Agency (EPA). Monitoring of research progress is particularly necessary in view of the broad scope and multidisciplinary character of the research program presented in the committee's first report (NRC 1998). As discussed in chapters I and 3 of this report, the first report's recommendations already appear to have had a substantial effect on research efforts of EPA and other agencies and organizations. Evaluating research plans and results requires the assessment of various levels of the research enterprise—ranging from individual research projects to broader programs—against research goals. The committee intends to review research progress for each of its ten recommended research topic areas, assessing research supported not only by EPA but by other agencies and organizations. The portfolio of research recommendations will also be updated periodically as new information is obtained (Chapter 3).

The committee formulated an approach for evaluating PM research progress that begins with the research-planning process and extends

[1] Some researchers use the term "atmospheric aerosol" or "ambient aerosol" to refer to airborne particulate matter. An aerosol is a suspension of a solid or liquid particles in a gas.

to evaluating the scientific knowledge and policy-relevant information that is obtained. As noted in the first report (NRC 1998), there are numerous uncertainties in the evidence available for airborne particulate matter, ranging from the source-receptor relationships to the biological mechanisms of injury (see Table 1.2). Effective management of risks related to airborne particulate matter will require research findings that significantly reduce uncertainties for the variety of atmospheric, exposure assessment, and health-effects questions relevant to standard setting and implementation.

The committee's first report (NRC 1998) presented three principal criteria for identifying research priorities for particulate matter—scientific value, decisionmaking value, and feasibility and timing. Cost was also considered. Those criteria guided the development of the committee's research portfolio, including the recommended research topics, estimated budgets, and approximate time frames for conducting research.

To reiterate, the criteria included

- **Scientific value** of the information, judged in terms of knowledge that fills important data gaps, provides information on cause-and-effect relationships, builds on previous findings, and contributes to the development of an integrated understanding of the health effects of particulate matter and gaseous copollutants.
- **Decisionmaking value**, or the usefulness of the results of particulate matter research findings to decisionmakers with a particular focus on reducing key uncertainties associated with regulatory standard setting and other risk-management decisions for the next review of the $PM_{2.5}$ NAAQS in 2002 and beyond.
- **Timing and feasibility**, the consideration that research needs to be operationally, technically, and financially feasible and conducted in a time frame responsive to decisionmakers' needs.

The committee concludes that the above criteria will serve equally well as measures for evaluating research progress, and it plans to apply them for that purpose.

The committee now introduces three additional criteria relevant to evaluating the planning, management, and implementation of the recommended research:

- **Interaction**—How well do the scientists involved in the research engage in collaboration across scientific disciplines, and are the scientific expertise, capacity and resources appropriately used to enhance scientific creativity, quality, and productivity?
- **Integration**—How effectively is research planning, management, and budgeting integrated in a joint process involving governmental and private organizations?
- **Accessibility**—How well is information about research plans, budgets, progress and results openly conveyed and shared among research organizations and other interested parties?

Interactions among investigators should be encouraged, and integration among organizations is needed to ensure that the return on the scientific investment is optimized. For example, sharing of experimental approaches and methods used in toxicological studies may avoid apparent confusion from the use of unnecessarily disparate experimental models. In addition, coordination of data-collection approaches and data bases improves the scientific basis for analysis by epidemiologists and statisticians. Early sharing of research plans and results across investigative groups can reduce potential confusion and can also stimulate advances in research protocols. Accessibility and dear communication of research plans and other information help to inform and assure stakeholders about the research program.

To achieve the overall objectives of the PM research portfolio recommended in the committee's first report, PM research must be viewed as a national effort, involving Congress and many agencies of the Executive Branch, as well as states and the private and nonprofit sectors. Integrated management of PM research is key to successful implementation of the research portfolio. Research on particulate matter is funded by several federal agencies, including EPA, Department of Energy, Department of the Interior, National Institute of Environmental

Health Sciences, National Oceanic and Atmospheric Administration, and others. The scope of funded research on particulate matter is expanding rapidly. The growing diversity of sponsors and the many different kinds of scientific investigations under way add to the complexity of the task of monitoring research progress and increase the need for federal interagency coordination and management of the effort.

Some aspects of airborne PM research are identified and coordinated across federal agencies at the level of the National Science and Technology Council and the White House Office of Science and Technology Policy. The Air Quality Research Subcommittee of the interagency Committee on Environment and Natural Resources (CENR) can provide a focal point for information dissemination among agencies and facilitates opportunities for research planning, primarily on atmospheric science research issues.[2]

In contrast to the coordination of atmospheric research, effective mechanisms have not been apparent for integrating the overall management of exposure and health-effects research with the physical-science activities in atmospheric research for airborne particulate matter across the federal government. Instead, individual researchers and agencies have organized *ad hoc* meetings or have exchanged information through informal networks or at professional meetings. No effective planning process has existed within the federal government to integrate the interrelated aspects of atmospheric, exposure, and health-effects research planning and management. In the committee's view, it will be very difficult for the PM research program to achieve its most significant objectives in the absence of an effective structure or process to operate across the agencies and disciplines to ensure common awareness of research activities, to engage in joint planning or funding

[2] CENR member departments and agencies include the Department of Agriculture, Department of Energy, Department of Health and Human Services, Department of Housing and Urban Development, Department of the Interior, Department of State, Department of Transportation, Environmental Protection Agency, National Aeronautics and Space Administration, National Science Foundation, Office of Management and Budget, Office of Science and Technology Policy, and the Tennessee Valley Authority.

of individual projects, or to provide effective and comprehensive coordination. This problem is by no means unique to airborne PM research. Multiorganizational integration and multidisciplinary interaction have historically been elusive goals in research. The various research organizations and scientific disciplines typically have different interests, funding sources, and professional cultures.

The committee was pleased to hear at its November 1998 meeting of a proposal to expand the charter of the Air Quality Subcommittee of the CENR to more actively encompass all federally sponsored PM research, including health research. That expansion should be encouraged to promote greater coordination of the resources of the federal government on PM research. CENR should move, as well, to establish a formal mechanism to enlist the collaboration of the nonfederal research community. One of the initial goals of this process should be to prepare a coordinated interagency strategy for implementing this committee's research portfolio. This strategy should be independently peer reviewed and should include

- A process and budget to implement the PM research portfolio recommended by the committee.
- The specific methods that will be used to coordinate research across agencies on a continuing basis.
- Strategies and mechanisms for leveraging funding with the federal sector, state governments, and the private and nonprofit sectors.

EPA is the agency with the largest mandate and budget for PM research. This NRC committee has received several briefings from staff of EPA's Office of Research and Development (ORD) and Office of Air Quality Planning and Standards (OAQPS) on the process of PM research planning and the status of individual research activities. Information obtained in those sessions, as well as the individual experiences of committee members in planning and managing research, provided a basis for analysis and conclusions by the committee.

The process of planning and managing PM research within EPA will undoubtedly produce many individual high-quality and policy-relevant research projects and results. EPA research administrators and staff have already demonstrated their willingness to use the committee's research recommendations as a template for the agency's PM research agenda. In the time since the committee's first report (NRC 1998), responsiveness on the part of EPA has been excellent. However, efforts to implement a multidisciplinary research program across the agency have revealed needs for improvement in the agency's overall research coordination approach for airborne particulate matter. Like the federal government overall, EPA has not had an effectively integrated structure or process through which to plan and implement the range of key atmospheric and health-related research across the scientific disciplines. In many cases, research within EPA is integrated among the disciplines through informal exchanges among researchers and *ad hoc* meetings and workshops. Although informal interactions are essential to the conduct of multidisciplinary research, the scope of the needed research on particulate matter requires a more formal process. Top EPA research and policy officials should participate and provide management guidance during all major decision points in planning, managing, implementing, and evaluating the PM research program.

EPA has begun to organize a formal process for integrating health and air-quality considerations in research planning for a key part of this program: PM chemical-speciation and supersites monitoring. At the committee's November 1998 meeting, in response to the recommendations of a July 1998 EPA/NARSTO workshop and comments raised by individual members of the committee at its September 1998 meeting, EPA presented a plan for a management approach developed by officials of the ORD and Office of Air and Radiation. The committee views this as a promising step toward integrated planning and management for these monitoring programs. The committee is also aware that EPA is coordinating plans for monitoring particulate matter and hazardous air pollutants. In addition, the agency needs to enhance its efforts to integrate the expertise and experience of the broader health, exposure, and atmospheric research communities into the ongoing design and implementation of the monitoring program.

In addition to an effective management structure, EPA's integrated planning process for research on particulate matter should include the following elements:

- Developing formally stated research objectives and time frames for each of the major research activities addressing particulate matter.
- Articulating the specific disciplines and skills needed to achieve the research objectives.
- Differentiating between the kinds of research that can be conducted intramurally and extramurally, including research best sponsored jointly with the private sector, other federal agencies, and nonprofit research institutions.
- Building specific planning mechanisms to design and coordinate research projects within EPA and between EPA and other institutions. This coordination should include relevant activities from other research programs, such as those planned for hazardous air pollutants.
- Maintaining an inventory of ongoing EPA and externally funded PM research projects. As stated in the committee's first report, such an inventory should be a continually updated status report of research in progress.
- Preparing periodic reports synthesizing the status of research activities and the progress being made to reduce key uncertainties, such as those identified in the committee's research portfolio. Such reports should not be mere compendia of ongoing research, but rather integrated summaries that enable investigators actively engaged in PM research, the broader scientific community, policymakers, Congress, and the public to understand major accomplishments and to identify key challenges still to be met.

Each of the above elements of the integrated research-planning process should contain information on resources invested or needed to carry out the plans. In addition, all aspects of the integrated plan should provide quick and easy access to relevant summary information for all interested parties.

In May 1999, EPA issued a revised draft research-strategy document (EPA 1999) for airborne particulate matter that was reviewed by CASAC on June 10, 1999. The date of issue of the document precluded review by this NRC committee in time to consider it in this report. The committee urges EPA to continue to update its PM research strategy regularly and, to make certain that what the strategy documents say and what is actually being done are closely linked.

In addition to federal agencies, airborne PM research is actively pursued by some states, the private sector, nonprofit organizations, and international research organizations, often in collaboration with one or more U.S. federal agencies. However, as in the case of the federal agencies, no effective ongoing mechanism is available for coordinated planning and integration of research across health, exposure, and atmospheric sciences.

NARSTO is the foremost existing example of such a mechanism, a public/private partnership with membership including government, industry, and academia throughout Canada, Mexico, and the United States, which was organized originally through the Air Quality Subcommittee of CENR. NARSTO has recently been discussing possible ways to link atmospheric research related to particulate matter with research on health effects. But no comparable private/public umbrella organization exists for the health and exposure sciences alone, or for all disciplines together.

Enhanced coordination and integration across all research-sponsoring organizations could provide substantial benefits in terms of leveraging broad-based support for key elements of the program, ensuring that the full research community is actively engaged in planning all relevant aspects of the research program, promoting accessibility to all results of the program, and avoiding unnecessary duplication of effort.

The committee supports recent statements by NARSTO that it will seek to reach out to the broader health and exposure-research communities to gain their perspectives in planning for upcoming atmospheric measurement and research programs. The committee also encourages the expanded CENR Air Quality Subcommittee to enhance its efforts by

- Formally including the full range of research-funding organizations in the development and implementation of research strategies.

- Ensuring that federal agency research leaders such as EPA, DOE, and NOAA convene targeted workshops regularly to bring together institutions and investigators involved in addressing specific research topics (e.g., the recent efforts to coordinate among all ongoing exposure assessment studies).
- Taking advantage of upcoming and regularly scheduled cross-disciplinary research meetings, such as the biannual Colloquium on Particulate Matter and Human Health, to bring together and exchange information among all active funders and investigators.
- To the extent appropriate, exploring the development of an ongoing health and exposure collaborative organization analogous to NARSTO that could continue collaboration across disciplines and facilitate collaboration between the atmospheric sciences and health and exposure communities.

Such mechanisms would help to ensure that to the maximum practical extent, the full national investment in PM research represents an integrated and collaborative program with the highest likelihood of providing timely, cost-effective, and useful results.

Much of the success of the PM research program will depend upon the ability of extramural scientists from a variety of institutions to collaborate across disciplines and organizations and to communicate the status and progress of their research in an effective and accessible manner. At present, neither EPA nor other major funding sources sufficiently facilitate such interdisciplinary interaction and communication. Consequently, researchers tend to remain within traditional disciplinary boundaries in developing new research proposals.

EPA's PM research program cannot be fully successful without stimulating agency and extramural scientists to cross disciplinary boundaries and work as teams to achieve concrete research objectives. Team-based research planning necessitates a new set of incentives that, where appropriate, motivates scientists to develop transdisciplinary proposals and teams, and in all cases, regularly provides opportunities for investigators to communicate and coordinate research across disciplines. The committee encourages EPA to create a formal plan to pro mote greater collaboration in planning and managing the PM research program. One opportunity to implement incentives lies in providing funding for planning interdisciplinary research through the EPA PM research centers program. In addition, where appropriate, EPA should encourage interdisciplinary research through its Science and Technology to Achieve Results (STAR) research grants program.

In its evaluation of PM research over the next 4 years, the committee plans to conduct an iterative, ongoing process of evaluation and will organize meetings, workshops, and other mechanisms to monitor research progress. As part of its evaluations, the committee plans to implement the following three steps:

- Array the results of particulate research sponsored by EPA and other institutions against the committee's recommended research portfolio to obtain an ongoing assessment of research gaps that need to be addressed.
- Compare research results against the six criteria presented at the beginning of this chapter. Particular priority will be assigned to evaluating the value of research results against the major issues that policymakers must address in setting and implementing standards.
- Conduct a series of public workshops to obtain information on the progress of EPA's PM research program and the programs of other funding agencies and organizations. Such workshops will include scientists, research managers, and policy experts from EPA, other federal and state agencies, universities, and the private sector, including industry and nonprofit organizations.

The committee believes there is an urgent need for the development of a comprehensive data base that identifies research that is under way, linking the research to the committee's ten portfolio recommendations and tracking progress. The committee has developed a prototype data base for this inventory but has concluded that further refinement and maintenance would exceed the committee's resources and charge. EPA should assume responsibility for further development and maintenance of the data base, perhaps in partnership with the Health Effects Institute (HEI), which, along with EPA, has already prepared summaries of research in progress. Without such an inventory, neither this committee, EPA, or other funding organizations will be able to monitor research progress adequately. In addition, the data base can facilitate the development of new research to address gaps and avoid inappropriate duplication of work already in progress. The committee has been informed by EPA and HEI that a planning effort for such a research inventory is in progress.

3

UPDATING THE RESEARCH PORTFOLIO

The committee intends its portfolio of PM research recommendations to be a dynamic document that will be updated and revised as research results are obtained and changing circumstances warrant. In this chapter, the committee updates and discusses further the ten high-priority research topics presented in its first report (NRC 1998). Most of the recommendations remain substantially unchanged, but research topics 3 and 4 are revised and renamed because of recent developments and further consideration of the current and planned emissions characterization, air-quality model development, and ambient monitoring activities of EPA and other agencies and organizations.

RESEARCH TOPIC 1 OUTDOOR MEASURES VERSUS ACTUAL HUMAN EXPOSURES

What are the quantitative relationships between concentrations of particulate matter and gaseous copollutants measured at stationary outdoor air-monitoring sites, and the contributions of these concentrations to actual personal exposures, especially for potentially susceptible subpopulations and individuals?

Background

As discussed in the committee's first report, currently available information is not sufficient to characterize the relationships of ambient air concentrations of PM and gases to actual human exposures that include indoor environments. Most people spend the majority of their time indoors exposed to a mixture of particles that penetrate from outdoors or are generated indoors. Personal exposures to certain air pollutants have consistently been found to differ from estimates based on corresponding outdoor concentrations. The differences are largely due to the variable contributions of outdoor air to indoor environments, the indoor fate of outdoor contaminants, and the substantial contribution of indoor sources and sinks to total personal PM exposures (Lioy et al. 1990). Studies have found that a significant fraction (50–90%) of small indoor particles have outdoor origins (Koutrakis et al. 1992; Clayton et al. 1993; Thomas et al. 1993). Once indoors, particles may deposit on surfaces, or they can be altered through volatilization, as with ammonium nitrate, or through reactions with other pollutants present indoors, as with neutralization of sulfuric acid by ammonia. Particles are further generated by myriad indoor particle sources, including cooking, resuspension, cleaning, tobacco smoking, pets, insects, and molds. The emission rates of most indoor-particle sources, however, have not been adequately quantified. Furthermore, factors that affect the contribution of outdoor particles to indoor concentrations have not been well characterized.

In its first report, the committee concluded that information is needed on relationships between particulate matter in outdoor air and personal exposure to particulate matter, especially for subpopulations that may be susceptible to the effects of PM exposures, such as the elderly, individuals with respiratory or cardiovascular disease, and children. Hypothesis-driven exposure studies must be designed to provide fundamental information on actual human breathing-zone exposures to PM and gaseous pollutants (NRC 1991). The recommended studies should be used to determine the exposure metrics that are most suitable for establishing exposure-response relationships. To attain these goals, the following specific research activities were recommended in the committee's first report:

- Field studies that quantify the contributions to personal exposures to PM and gaseous pollutants attributed to outdoor ambient air and to the penetration of ambient air indoors.

- Longitudinal panel studies, in which groups of individuals are studied at successive points in time, to examine interpersonal and intrapersonal variability, as well as seasonal and temporal variability in PM exposure.
- Analyses of information collected from such field and longitudinal studies to determine the contributions of outdoor versus indoor sources for each pollutant, and to examine the degree to which the use of more accurate exposure information would, or would not, alter the findings of epidemiological time-series studies concerning particulate matter and adverse health effects.

The sampling of particulate matter should include measurements of $PM_{2.5}$ and $PM_{10.}$ as well as other relevant descriptors of particulate matter that might be of value in understanding the impact of particulate matter on human health. The design and execution of a typical panel exposure-assessment study will take approximately 3 years for subject recruitment, field measurements, collection of time-activity data, and data analysis. This research should include potentially susceptible populations in various geographical locations.

Update

At the committee's June 1998 meeting, Dr. Judith Graham of EPA's Office of Research and Development (ORD) presented a particulate-exposure research plan initiated by EPA in response to the committee's first report. That plan includes substantial changes in EPA's allocation of research resources that the committee finds highly commendable. The program will bring about new in-house and extramural research projects and related personnel changes that are highly consistent with the committee's recommendations. Much of the plan has been implemented and has begun to yield results. Overall, these recent efforts by EPA to support human exposure-assessment research for particulate matter are substantive and promising.

In budget terms, Congress increased the resources devoted to research in this area from $3.6 million in the President's proposed budget for Fiscal Year 1999 to $8.2 million in 1999 appropriations, and EPA has proposed a budget of $7.9 million for Fiscal Year 2000 (see Table 1.4).

Studies conducted by EPA scientists in EPA laboratories will characterize microenvironmental particulate exposures to provide information for the development of exposure models. They will characterize and assess human exposures to fine particles to enhance understanding of sources of these particles and their spatial and temporal profiles. Using an experimental model home, EPA scientists will also investigate processes governing the penetration of outdoor particles into indoor environments and their deposition onto indoor surfaces to determine the contribution of outdoor sources to indoor and personal exposures.

EPA is establishing cooperative agreements with universities to characterize the exposures of sensitive subpopulations to particulate matter and related gaseous pollutants. Under these cooperative agreements, studies will be conducted in several urban environments that are characterized by different particle composition and meteorological conditions, including New York, Boston, Atlanta, Los Angeles, and Seattle. The main objectives of these studies are (1) to characterize the personal particulate and gaseous exposures of sensitive as well as healthy individuals; (2) to identify factors affecting such exposures and their corresponding personal exposure versus outdoor concentration relationships; (3) to develop models to predict individual exposures and population exposures to fine-particle mass; and (4) to determine the contribution of outdoor and indoor sources to personal particulate exposures. Under one of the cooperative agreements, studies will also determine the correlations between personal particulate and gaseous exposures.

In each of the cooperative agreements, a large number of personal, indoor, and outdoor measurements will be made in winter and summer for several susceptible subpopulations, including children, senior citizens, asthmatics, and individuals with chronic obstructive pulmonary disease and myocardial infractions. Together, these studies will provide a powerful data base that can be used to characterize particulate exposures for susceptible populations, to determine inter-and intrapersonal variability in particulate exposures, and to quantify and statistically characterize the measurement error that results from exposures estimated from single outdoor monitoring sites. These findings will be useful for the interpretation of results from epidemiological studies and for the accurate determination of exposure-response relationships.

In addition to the mass-based $PM_{2.5}$ monitoring program being implemented for regulatory compliance assessment, EPA's air regulatory program office is planning to develop two additional particle-monitoring programs: a chemical-speciation monitoring program and a supersites program. The Primary objective of the speciation-monitoring program is to measure particle composition to aid states and EPA to develop and evaluate particle control strategies. The main objective of the supersites program is to develop a better scientific understanding of source-receptor relationships through intensive monitoring of several representative airsheds using state-of-the-art sampling and analytical techniques.

In response to the committee's first report and other considerations, EPA convened expert panels to provide design guidance for both of the additional monitoring programs. Both panels included exposure scientists who contributed to the final monitoring design. It is anticipated that these monitoring programs will produce data that may be used by future particle-exposure studies, because the networks will monitor the spatial and temporal variability of particle mass and its components in several locations throughout the United States. The committee also urged the integration of exposure and health-effects studies into the supersites program. The committee believes that stronger interactions between the atmospheric-modeling and health-science communities are needed to ensure that the programs will be of significant value.

EPA's National Exposure Research Laboratory is hiring additional exposure-assessment experts who will conduct and oversee related research activities. These experts will be assisted by scientists within EPA's exposure and engineering laboratories who have been assigned to work on particle-exposure projects. Further support will be provided by several postdoctoral fellows who have recently joined EPA to conduct particle-related research.

In addition, EPA has begun to improve coordination of its exposure research activities with those conducted by other organizations such as the Health Effects Institute (HEI), Electric Power Research Institute

(EPRI), and American Petroleum Institute (API). This coordination will help to ensure that cost-effective research is being conducted to address all particulate exposure research needs.

The committee believes that the EPA efforts described above will make it possible to address most of the exposure research needs included in Research Topic 1 of the committee's first report.

The exposure-assessment research recommendations in the committee's first report placed initial emphasis on needs for short-term measurements of personal exposure to be compared with outdoor exposures to particulate matter in a cross section of locations, using sensitive subgroups and healthy members of the general population. The next set of exposure measurements needed will be concurrent long-term studies of population exposure to particulate matter and copollutants. The design and resources required will be dependent upon the results of the near term research described in the first report. Of particular interest will be the results obtained to define personal exposure to particulate matter and its constituents and to identify biologically active agents and mechanisms of action.

RESEARCH TOPIC 2: EXPOSURES OF SUSCEPTIBLE SUBPOPULATIONS TO TOXICPARTICULATE-MATTER COMPONENTS

What are the exposures to biologically important constituents and specific characteristics of particulate matter that cause responses in potentially susceptible subpopulations and the general population ?

Background

In its first report, the committee recommended a group of studies to begin about the year 2001, as information improves on PM constituents and as specific chemical constituents or particle-size fractions are indicated as plausible causal agents. These studies should quantify exposures to those constituents for the general public and susceptible subpopulations. The process of obtaining information on such exposures will be iterative, with information developed from earlier studies guiding the planning of later studies. Population-based field studies will provide information on the distribution and intensity of exposure of the general population to experimentally defined particle components and size fractions. The studies should be conducted for statistically representative groups of the general population and for potentially susceptible subgroups. The studies could be coupled to health-outcome investigations, but they should be designed to determine the extent to which members of the population contact these biologically important constituents and size fractions of concern in outdoor air, outdoor air that has penetrated indoors, and air pollutants generated indoors.

In its first report, the committee recommended that the following specific research tasks be addressed in Research Topic 2, after obtaining and interpreting results of studies and information from Research Topic 1:

- Measure population exposures to the most biologically important constituents and size fractions of particulate matter. These exposure studies should include members of the general population and potentially susceptible subgroups, using personal-monitoring studies and ambient stationary sites to examine the contributions of outdoor pollutants to total personal exposure.
- Refine sampling and analysis tools to permit their routine application for the determination of biologically important chemical constituents and size ranges of particulate matter.

Some of the recommended population-exposure studies could be initiated soon, but a more targeted set of studies under this research topic should await a better understanding of the physical, chemical, and biological properties of airborne particles associated with the reported mortality and morbidity outcomes. The exposure research should then be conducted expeditiously to inform decisions on source-reduction strategies. Focusing on the specific toxicity-determining attributes of particulate matter will be essential to make population-exposure studies cost-effective.

Update

Research Topic 2 of the committee's first report called for a more comprehensive approach to particle-exposure assessment, emphasizing the need for characterization of particulate exposures of large populations. Most of the research activities included in this topic are not expected to commence until about 2001, when information from toxicological studies becomes available. However, the committee recommends that it would be beneficial to start small-scale studies immediately to develop new tools and information to design the new generation of exposure research projects. Examples of such studies include the following:

- *Comprehensive intercomparison study of personal samplers*—Intercomparison studies of personal samplers are necessary to evaluate the performance of personal sampling devices and to ensure that data sets from different exposure studies are comparable.
- *Temporal-variability studies of personal exposures*—Studies examining temporal variability in personal exposures will enable better information to be obtained about the duration and frequency of human exposures. The National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ was based on 24-hour time intervals because epidemiological studies examined the exposure-effect association using 24-hour ambient particle concentrations and health measurements. However, future toxicological investigations and future epidemiological studies may provide a better scientific basis for choosing the appropriate time interval of the exposure.
- *Exposure misclassification studies*—As mentioned previously, several exposure studies will examine the relationship between personal exposures and outdoor concentrations. Will these data be sufficient to investigate the effect of exposure misclassification? Do we need to perform additional studies to provide complementary data sets? To make this decision, epidemiologists and exposure scientists will need to work together to develop the analytical framework for this research. Care should be taken to define the

spatial and temporal variability of outdoor, indoor, and personal exposure concentrations.

- *Pilot studies characterizing the physicochemical characteristics of pollutants to which individuals are exposed*—Pilot projects investigating the physicochemical characteristics of pollutants to which individuals are exposed will make it possible to identify factors affecting exposures to different particle components and sizes. This is necessary for the design of the future population-exposure studies. Such pilot studies should include development of sampling and analytical methods for biological-particle components and refinement of questionnaires for selection of representative populations.
- *Individual and population-exposure modeling studies*—The development of individual-and population-exposure models will allow personal exposures to be characterized for large study populations without the need for expensive personal monitoring. These models will likely use information on human activity patterns and microenvironmental concentrations or characteristics to predict short- and long-term exposures.

REFOCUSING RESEARCH TOPICS 3 AND 4

Sound strategies to manage PM risks will require an improved understanding of relationships among the sources of particulate matter, the atmospheric processes that transport and transform it, and the concentrations of particulate matter to which populations are exposed. Computer models based on such understanding will provide state and local air-quality agencies with the tools necessary to develop state implementation plans that control emissions in ways that (1) focus on the most biologically active and relevant components of the PM mixture, and (2) identify cost-effective strategies for reducing the exposure of the general population to those emissions.

In preparing this second report, the committee reviewed current and planned emission-source characterization, model development, and ambient monitoring activities of EPA, other federal, state, and local agencies, the research community, and the private sector. The committee received briefings from the CENR Air Quality Subcommittee, NARSTO, and EPA's Office of Air and Radiation (OAR) on plans for speciation monitoring and supersite monitoring. Based on that information, the committee has refocused and renamed topics 3 and 4 of the research portfolio to integrate more closely these implementation-related research activities, including the development and evaluation of emission-source characterization techniques (see revised Research Topic 3), and source-oriented and receptor-oriented air-quality models (see revised Research Topic 4).

The attainment of national PM risk-reduction goals will require active collaboration (see Figure 3.1) among the research community, OAR and ORD of EPA, other federal, state, and local agencies, and the private sector. Research efforts will be needed to develop and evaluate source-measurement techniques and source-oriented and receptor-oriented models, as described below in revised topics 3 and 4. However, the ultimate success of these research efforts will depend in large part on the collection of key data on particle and precursor concentrations and composition, regardless of whether those data are collected by research organizations, federal and state regulatory programs, or others. Specifically, these efforts will require

- Collection of emissions data for major categories of sources, and development of the speciated and size-resolved emission inventories necessary to operate and evaluate particle models.
- Collection, through compliance, speciation, and supersite monitoring programs, of the meteorological and air-quality data that will be necessary to evaluate the performance of particle models.

The paradigm presented in Figure 3.1 calls for a synchronization of activities and extensive collaboration among atmospheric, exposure, and health scientists, as well as among federal, state, and private research and control programs. Efforts by health-effects and exposure-

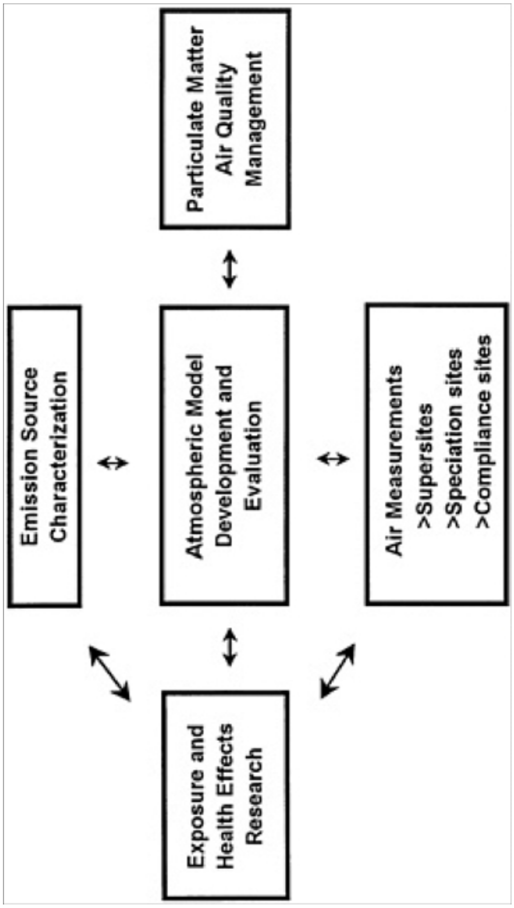

Figure 3.1 A paradigm for scientific and technical activities related to particulate matter.

assessment scientists are needed to refine (or redefine) the list of particle properties for which atmospheric scientists and environmental engineers and modelers must account. Under the present, real-world constraints of limited time and finite resources, it is essential that efforts be targeted at the most biologically active components of airborne particulate matter. Plausible candidates for biologically active components include several metals, organics, acid sulfates, biogenic agents, and ultrafine particles of any composition.

The distinction with broadest implications for air-quality management is that between primary and secondary particulate matter. Most acid sulfate and some organic material is not directly emitted, but instead is produced by chemical reactions after emissions, forming secondary atmospheric particles over time. Secondary particles generally exhibit more uniform concentration fields, because the processes of chemical formation and physical dilution proceed simultaneously to distribute the product species throughout large air volumes. Secondary particles are major contributors to the regional haze monitored by nonurban samplers. Primary particles are found instead in highest concentrations near their sources, where the least dilution and sedimentation have occurred. Primary particles thus tend to be more important in the atmospheres of urban-industrial population centers. A strategy for the management of secondary particulate matter must be regional in scope, while a strategy for primary particles could legitimately emphasize concentration "hot spots."

A critical issue in the development of source-receptor modeling tools is the relative roles of source-oriented and receptor-oriented approaches. Source-oriented models, which range from simple plume-dispersion formulae to complex grid models, start from emissions rates and predict expected ambient concentration fields. The models incorporate mathematical representations of critical chemical and physical processes to simulate the transport and transportation of particulate matter in the atmosphere. Receptor-oriented models (e.g., chemical mass balance) begin with particle chemical composition measured in ambient air and at various sources, and infer the relative source contributions to each individual ambient sample by calculating the mixture of effluents needed to account for the observed chemical composition. The models rely on empirical observations to sort out source-receptor relationships statistically. For stable primary particles, receptor models yield credible and precise apportionments of ambient particulate matter between certain contributing source categories. For secondary particles, on the other hand, the transformations by which they are formed are difficult to account for outside the framework of a source-oriented model that incorporates the relevant atmospheric processes.

In its first report, the committee commented upon EPA's plans for the implementation of the national $PM_{2.5}$ monitoring system, including some 1,500 compliance and speciation monitors and 5–7 supersites. Based on that initial review, the committee stated

> "The committee is concerned about the scientific value of the data to be collected in these efforts if such monitoring is fully planned and implemented before some of the immediate research priorities are addressed and data gaps are filled. Moreover, as a secondary but critical goal, such a monitoring system should also be designed to support relevant health-effects, exposure, and atmospheric-modeling research efforts, or else the cost of some important research will increase substantially because of the need for additional monitoring." (NRC 1998, p. 9)

The committee also noted

> "Greater use of continuous (hourly) monitors would help determine the times of day and the exposures of people who are commuting, working, or exercising outdoors. More chemical characterization of particulate matter would help to enable testing of more specific indicators than $PM_{2.5}$ mass alone." (NRC 1998, p. 10)
>
> "Data-collection efforts for model development and testing will require substantial additional resources if the data need to be collected independently of EPA's $PM_{2.5}$ monitoring program. The additional costs could be as high as $2.0 million to $10 million per urban area." (NRC 1998, p. 59)

After its first report was released in March 1998, the committee met three times with staff from EPA and other agencies and organizations to review the state of the monitoring program and to evaluate the degree to which EPA would be addressing the concerns expressed above. In addition, committee members participated in a workshop held by EPA and NARSTO on July 22–23, 1998, and a workshop held by NARSTO on January 27–29, 1999, that brought together federal, state, and local monitoring specialists with members of the health, exposure-assessment, and atmospheric-modeling research communities to provide guidance for the implementation of the supersites program, and for the integration of that program into the broader monitoring system.

Based on these reviews, the committee found that EPA made several noteworthy adjustments in the plans for the atmospheric-monitoring programs that will improve its ability to provide data useful to meet key research needs. Specifically, EPA reported that it has increased the number of "continuous" $PM_{2.5}$ monitoring sites from 50 to more than 100 nationwide, and it has revised plans for the routine speciation-monitoring program to include 44 trend sites where speciation will occur every third day, and ten sites where PM chemical-speciation measurements will be made every day. These changes will improve the ability of the monitoring system to provide the measurement data necessary to (1) test and characterize the Federal Reference Method for measuring $PM_{2.5}$, (2) conduct more-detailed health and exposure research aimed at specific components of particulate matter, and (3) provide initial data for operation and testing of source-oriented and receptor-oriented models. Whether the capability to support health studies and model evaluation studies will actually be used for these purposes remains unclear at present. The committee urges EPA to obtain greater input from the atmospheric-modeling and health-science communities in the design of these monitoring programs, especially the supersites program.

In the following pages, the committee refocuses and renames research topics 3 and 4 from its first report to reflect recent developments and additional information about EPA's revised plans for the $PM_{2.5}$ monitoring network. Research topics 3 and 4 are intended to describe an entire realm of implementation-related research (i.e., research related to implementation of the $PM_{2.5}$ NAAQS). In this report, certain methodological development needs cited in the previous report have been reallocated to other tasks in the portfolio with which they are closely aligned. Specifically, in the following pages, the committee

- Makes more explicit its earlier calls for enhanced source-emissions characterization by refocusing Research Topic 3 on the research needed to develop sophisticated techniques to characterize not only source emissions of particle mass, but other characteristics and components of the emissions as well.
- Refocuses Research Topic 4 on the development and evaluation of source-oriented and receptor-oriented models and increases somewhat the resources recommended for this topic to reflect a better understanding of areas where the planned EPA monitoring will not provide adequate data for model evaluation and where additional research measurements may be necessary (NRC 1998, p. 59).
- Reallocates the development of exposure-assessment technologies previously contained in research topics 3 and 4 to the year 2000 for topic 2 (where those techniques will be applied), and the development of advanced analytic methods for monitoring biological responses to toxic PM components.

In contrast to the other research topics, which are simply updated in this chapter, the revised topics 3 and 4 are discussed more expansively in the following pages, using the format in which topics were originally presented in the committee's first report.

In addition, as noted above, the committee continues to see the need for a substantial investment from federal and state regulatory programs and other organizations in conducting source characterizations, developing emissions inventories, and providing the detailed, sustained, and quality-assured monitoring data that will ultimately be necessary to operate and evaluate any models developed under Research Topic 4. Absent of these investments, the research program described in topics 3 and 4 would be substantially more expensive, or it will be unable to accomplish the goal of providing reliable models in time to assist the states in developing effective state implementation plans.

At its September 1998 meeting, the committee received an updated briefing on the status of the ambient-monitoring programs, including the timetable and organizational structure for implementing the supersites in the context of the larger health, exposure, and atmospheric research program now underway. Several scientists commented previously that the program lacked (1) coordination and leadership to bring together the research program staff and air regulatory staff who must implement it, (2) ongoing mechanisms to provide continued interaction and linkage with outside health, exposure, and atmospheric research communities, and (3) a timely, but deliberate, implementation schedule to ensure that such sites will be an integral part of the measurement program. In response, at the committee's November 1998 meeting, EPA presented a revamped structure and timetable for implementation. The committee commends EPA for taking steps to promote better integration of this important measurement effort into the implementation of the overall research program. In addition, the committee wishes to emphasize the importance of regularly incorporating the experience and expertise of the outside health-and exposure-research communities into the planning and implementation of this program (see Chapter 2).

RESEARCH TOPIC 3 (REVISED): CHARACTERIZATION OF EMISSIONS SOURCES

What are the size-distribution, chemical-composition, and mass-emission rates of particulate matter emitted from the collection of primary-particle sources in the United States, and what are the emissions of reactive gases that lead to secondary particle formation through atmospheric chemical reactions?

As discussed above, this is a revised and renamed research topic, replacing Research Topic 3 in the committee's first report.

Description

Airborne particles are emitted from a large variety of anthropogenic and natural sources. Natural sources are many, including forest fires and wind erosion. In cities, several hundred different particle source types can be broadly classified into motor-vehicle exhaust sources, stationary fuel-combustion sources, industrial processes, and fugitive area wide sources. Many different activities fall within each of these categories. Motor-vehicle exhaust emissions arise not only from automobiles and light-duty trucks, but also from heavy-duty diesel trucks and buses, railroad locomotive engines, engines in nonroad construction equipment, marine diesel engines, and aircraft engines. Stationary fuel-combustion sources include boilers, refinery process heaters, and gas-turbine engines—each capable of being built to burn a variety of fuels. Industrial processes range from rock crushers that emit large mineral-dust particles to chemical processes that emit finely divided acid mists and metal-melting furnaces that emit fumes containing fine particles of toxic metals. The category containing fugitive area wide sources is particularly difficult to characterize thoroughly. It includes all of the particle emissions that result from personal activities and many commercial activities in the community, such as the particles released from food cooking, fireplaces and wood stoves, paved and unpaved road dust, construction and demolition dust, wildfires, backyard leaf burning, structural fires, and so forth (Hildemann et al. 1991).

Particles that are directly emitted from sources are transported through the atmosphere in the presence of chemically reactive gases including ozone, sulfur dioxide (SO_2), oxides of nitrogen (NO_x), ammonia, and volatile organic compounds. Over time, the directly emitted particles become coated with the low-vapor-pressure products of atmospheric chemical reactions involving the pollutant gases mentioned above. As a result, the particle-mass concentration in the atmosphere may increase as primary particles incorporate additional sulfates, nitrates, and organic compounds. The source emissions of reactive gases that act as secondary-aerosol precursors must be characterized if their role in the particle formation process is to be understood and controlled.

Traditional source-test methods for particulate matter typically have been used to determine particle-mass emissions aggregated over all particles smaller than a certain size, with little regard for determination of the chemical composition of the particles. Such measurements are clearly inadequate to support management strategies targeted at specific components or characteristics of particulate matter that health scientists may come to identify as biologically important. Measurements that lack detailed information on particle size and chemical composition are also inadequate to the needs of atmospheric scientists seeking to understand details of atmospheric transport and transformation. For example, atmospheric models that are capable of tracking the accumulation of gas-phase atmospheric reaction products onto preexisting particles require that the size distribution of the emitted particles be known over narrow slices of the particle-size distribution (typically in 15 particle-size intervals or, alternatively, as a continuous size-distribution function over the particle-size range from about 0.01 μm to at least 10 μm in diameter). The chemical composition of the particles in each size interval must be specified to calculate the water-uptake and chemical-thermodynamic status of the particles, which greatly influence whether the particles will interact with soluble pollutant gases. The organic chemical composition of the particles needs to be known to estimate the quantities of vapor-phase organic compounds that will be absorbed into the particles during transport through the atmosphere. These needs have not been met by current monitoring methods; further research and methods development are needed.

Measurement of the size distribution and composition of fine-particle emissions from sources is difficult because many of the organic compounds that will come to equilibrium in the particle phase are still present in the gas phase at the high stack-gas temperatures where source samples must be collected. This problem is being addressed through the use of dilution tunnels that simulate the process of plume cooling by dilution in the atmosphere by mixing a great excess of clean dilution air with the source effluent before making the particulate-source measurements. This serves two purposes. First, it reduces the source effluent to near-ambient temperature and pressure, thereby causing semivolatile gases that will form particles by condensation in the plume immediately downwind of the source to migrate into the particle phase before the particle samples are collected. Second, it creates sampling conditions under which the sophisticated instrumentation that has been developed for characterizing the size and composition distributions of atmospheric particles can be applied to the problem of measuring particles as they are emitted from their original source.

Recommended Research

The research source-testing procedures mentioned above first have to be evaluated, possibly modified, and then specified in the form of a set of standard methods. Many decisions will have to be made about the best protocols and instrumentation to be used for making particle-size distribution and chemical-composition measurements from the diluted source exhaust.

Following the selection of standard methods, the population of several hundred different types of air-pollution sources will have to be characterized—for the first time, in many cases. In addition, new source-test methods will be needed for accurate and simultaneous determination of the emissions rates of the important gas-phase particle precursors; the existing database is particularly weak as it applies to emissions of ammonia and semivolatile organic vapors (generally consisting of vapor-phase organic compounds with greater than 10 to 12 carbon atoms).

Once new emissions data have been collected for a sufficient number of geographically representative examples of the relevant source types, the data must next be compiled into spatially and temporally resolved comprehensive emissions inventories that represent the emissions from all sources in the country in a way that these data can be used by air-quality scientists and by the regulatory agencies that must draft emissions control plans. Over time, adjustments in the national emissions inventory may be needed to account for any substantial changes in regional emission patterns that may have occurred after source testing was performed.

Scientific Value

Knowledge of the size distribution and chemical composition of PM emissions, as well as the emission rates of reactive gases that act as PM precursors, is basic to the understanding of fine particles in the atmosphere. This understanding involves cause-and-effect relationships that can be verified with atmospheric observations only if emissions are accurately specified. Confidence in the air-quality models emerging from decades of research on the individual physical processes that govern atmospheric chemistry, aerosol thermodynamics, and atmospheric transport and removal will rest on the ability of such models to predict observed ambient particle characteristics from these emissions inputs. Concurrently, knowledge of the size and composition of the emitted particles is needed if the particle-exposure systems used by laboratory toxicologists are to be chosen in a way that accurately represents the relevant differences in the particles emitted from the many different source types.

Decisionmaking Value

Decisions about the relative mix of emissions control measures needed to attain compliance with ambient air-quality standards for particulate matter cannot be made with any confidence unless the emissions themselves have been quantified and the sources of such emissions have been identified accurately (also see Research Topic 4).

Feasibility and Timing

A deliberate intercomparison of alternative measurement methods should first be conducted to select standard source-testing protocols that are suited to obtaining high-resolution data on particle size and composition. Thorough evaluation of the alternative measurement methods under actual field-sampling conditions is a difficult research task that could easily take 2 to 3 years to complete.

Following specification of standard source-testing methods, the research must then turn to quantifying through actual tests the particulate-emissions characteristics of the relevant populations of emissions sources. The emissions inventories maintained by the states and by EPA contain at least 350 source categories for which emissions-source profiles must be assigned (EPA 1985, 1995). If some PM components are subsequently found to be biologically more important than others, it might be possible to focus on a subset of these. Somewhere between 25 and 75 source types probably must be characterized in the near future to meet the goal of accurately representing the sources contributing about 80% of the particle mass present in the atmosphere.

At the outset of this source-test program, the newly developed procedures will be in use for the first time, and the first few groups of sources tested should be viewed as part of the research-and-development program leading to the establishment of the new source-testing protocols. Once the application of the procedures has become routine, the source-testing program should be completed as a part of federal and state regulatory programs. If source-testing programs were to be done over 5 years, then from 5 to 15 source-testing campaigns directed at different source types would have to be conducted per year. Conversion of the information on the emissions from representative sources into a spatially and temporally resolved emissions inventory for the United States would then require about 2 to 3 additional years of effort by a team of individuals skilled in the use of modern geographic information systems (GIS) technology. The entire national emissions inventory program thus will require about a decade for completion.

Cost

One reason emissions data bases generally lack complete information on particle emission rates as a function of particle size and composition is that source tests are complex and expensive. Most regional studies aimed at atmospheric-particle characterization and modeling in the past have neglected to undertake a parallel program of research-quality source emissions measurements, mainly because source measurements are so difficult and expensive to conduct. A thorough evaluation and intercomparison of alternative source-testing methods for determination of PM size and composition—followed by execution of enough real source tests to establish the viability of the methods under actual field-operating conditions—will probably require an expenditure of approximately $2.5 million per year over about 4 years. Many side-by-side source tests will need to be conducted to compare the alternative methods on stationary, mobile, and fugitive sources, and for particles and reactive gases.

Beginning immediately, EPA should create an interim national emis sion inventory for particulate matter and gaseous particle precursors. This interim inventory should provide the best practicable, spatially and temporally resolved account of the size distribution and chemical composition of particle emissions and gaseous particle precursors given current pollutant source test data. The interim inventory is needed by 2002 to support the initial testing of source-oriented models for particle size and composition that in turn may be needed for control-strategy planning. The cost of this interim emissions inventory effort is estimated at $1 million per year for about 4 years. Once the source test program has been turned over to the regulatory arm of EPA, application of the new standard test methods to the characterization of emissions from a representative selection of examples of a single source type (e.g., oil-fired utility boilers and railroad locomotives) will probably cost $300,000 to $500,000 per source class if a thorough job is done using professional research contractors, or possibly as little as $100,000 per source class if the research is performed mostly by teams of university graduate and postdoctoral scholars. At the rate of 5 to 15 source classes per year, this source-testing effort could easily cost $5 million per year for 4 to 5 years (the range of costs is fairly wide, spanning values from as little as about $1 million per year to as much as $7.5 million per year, depending on how the work is commissioned). Compilation of the full national emissions inventory will probably cost about $1 million per year for about 3 additional years.

Thus, the overall cost estimate for research to develop standard source test methods and to apply those methods to establish their viability under field sampling conditions is $2.5 million per year for 4 years. That research must be accompanied by technical support work by federal and state regulatory programs at about $5 million per year for about 5 years for testing of the most important source types plus about $7.0 million from regulatory programs for the compilation of an interim PM emissions inventory and a national emissions inventory based on the new source test data.

The estimate of $2.5 million per year for 4 years for research on source-test methods is shown in the committee's updated portfolio in Table 3.1. The cost of continued application of the source-test methods is not built into the research budget, because that activity is viewed by this committee as an appropriate task for federal and state regulatory programs. Nevertheless, that activity (represented in Table 3.2) must be undertaken, because the revised emissions inventory lies on the critical path toward timely completion of necessary research into the development and evaluation of models that relate source emissions to ambient air quality.

RESEARCH TOPIC 4 (REVISED): AIR-QUALITY-MODEL DEVELOPMENT AND TESTING

What are the linkages between emission sources and ambient concentrations of the biologically important components of particulate matter?

As discussed above, this is a revised research topic, replacing Research Topic 4 in the committee's first report.

Description

Airborne particulate matter results from direct emissions of primary particles and atmospheric formation of secondary material (Finlayson-Pitts and Pitts, 1986). In the atmosphere, emitted particles and reactive gases undergo transport and dispersion, chemical and physical processes, and deposition to the earth's surface. Transport and dispersion describe the horizontal and vertical motions of gases and particles due to winds and turbulent diffusion. Chemical transformations include reactions between gases, on particles, and in cloud and fog droplets. Such transformations also involve thermodynamic equilibrium between the gas phase and particle phase. Physical processes of gas-to-particle conversion and growth include nucleation of vapors to form particles, condensation of gaseous species onto existing particles, and, under high-humidity conditions, the activation of particles to form cloud and fog droplets. Deposition, wet and dry, removes the particles from the atmosphere. Dry deposition involves turbulent and molecular diffusion for very small particles and gravitational settling for larger particles. Wet deposition is the removal by falling rain and snow of their nuclei and intercepted particles. The relative importance of these chemical and physical processes determines the contributions of distant and local sources to particulate composition and size structure at any given site.

Due to the complex, nonlinear processes involved in atmospheric-particle formation, source-oriented models are the only comprehensive tools available to develop air-quality management strategies for reducing ambient levels of secondary particulate matter (NRC 1993). However, the source-oriented modeling approach is very resource-intensive and relies on comprehensive, accurate descriptions of the relevant source emissions, chemical reactions, and physical processes. Receptor models complement source-oriented models by providing independent assessments of the emission sources contributing to measured concentrations of particulate matter and its components (see Subtopic 4b). Both modeling approaches require special measurements of emissions, meteorology, and gas and particle concentrations before they can be applied and tested.

Because it is not possible at this time to determine which of the many components of particulate matter will ultimately be found to contribute significantly to adverse health effects, models are needed that will describe a broad range of species and detailed particle sizes. Therefore, it is necessary to proceed with the development and testing of sophisticated speciation and size-resolved models so that they will be available as biologically important particulate species are identified. Thus, an iterative approach will be needed to focus modeling efforts on biologically relevant species.

Before any model can be used with confidence, its theoretical soundness and computational integrity must be evaluated, and its performance must be compared with full sets of independent data. A comprehensive source-oriented model evaluation program requires (1) urban or regional field experiments to characterize four-dimensional (space and time) ambient gas-concentration and particle-concentration fields, with the particles resolved by size and chemical composition; (2) a spatially and temporally resolved emission inventory for all particle types and precursor gases; and (3) four-dimensional meteorological fields. Subsets of these measurements suffice for most receptor-oriented models.

Source-oriented models are tested for their ability to reproduce observed concentrations of precursors and products from emissions and meteorological inputs. Receptor-oriented models are tested for the consistency of their concentration-derived inferences with observed emissions and meteorology. Comprehensive measurements, focused on individual representations of chemical and physical processes, are needed for diagnostic testing of both model types. Also, source-oriented models must agree with results from receptor-oriented models. In many areas, the comprehensive field-measurement programs needed for application of source-oriented models may not be possible because of resource constraints, and receptor models, which have less-intensive input data requirements that can be satisfied with the PM speciation network, may be the only modeling tool available.

The first generation of source-oriented particle models has undergone evaluation for a limited number of meteorological conditions and geographic areas. Although the model performance results for these complex systems are encouraging, they still fall well short of results for ozone models (Seigneur et al. 1997). The most extensive testing has utilized databases collected in southern and central California, and clearly there is a need for field experiments in other parts of the United States. The CMB (chemical mass balance) model is a receptor-oriented model that is EPA-approved for primary-particle applications. Quantitative receptor-oriented models for secondary particles have yet to be successfully demonstrated.

4a. Source-Oriented Models

After more than 20 years of development, source-oriented models are now routinely used to predict the effectiveness of emission-control strategies for ozone. Although many of the chemical and physical processes affecting particulate matter are already treated by source-oriented models for ozone, major complications arise from the finer spatial resolutions, longer time scales, and attention to phase partitioning required in particle models. As a result, source-oriented models for particulate matter are still in their formative stages. However, a new generation of source-oriented models that include descriptions of all the relevant processes is being developed (Seigneur et al. 1997).

Spatial scales for ozone modeling and particle modeling have traditionally been on the order of hundreds to a few thousands of kilometers, with grid elements ranging from 4 km^2 to 20 km^2. These dimensions appear to work reasonably well for secondary pollutants, but spatial gradients for primary particles can be much steeper. At spatial scales smaller than the size of grid elements, the ability to represent key transport, dispersion, and deposition processes accurately is lost. Thus, the applicability of grid models to the study of primary pollutants is uncertain, as the ability to provide emissions and meteorological data at finer resolution is doubtful. One possible approach to overcome this limitation of grid models is to use speciated rollback of receptor-modeling results for primary particles with unique chemical-and physical-size fingerprints (NRC 1993).

Source-oriented models, with their intensive computational needs and their extensive requirements for emission and aerometric inputs, are best suited for episodes of a few days' duration. However, the annual-average $PM_{2.5}$ NAAQS appears likely to be more difficult to meet than the 24-hour-average standard for many urban areas. An annual average can be constructed by applying the model to a representative series of episodes or by employing a simplified version of the model for each day of the year. These approaches have only recently been demonstrated for ozone models (Winner and Cass 1999) and present a more difficult problem because of the greater diversity of particle episodes (Dolislager and Motallebi in press).

Water is associated with many of the particles found in the atmosphere (Saxena and Hildemann 1996). Source-oriented models treat processes of particle growth and evaporation due to water and other components with a thermodynamic-equilibrium model. Such thermodynamic models appear to be satisfactory for inorganic components of the urban atmosphere. However, models of the thermodynamics of organic components are still under development. In addition, models that incorporate the thermodynamics and aqueous-phase chemistry of cloud and fog water droplets are still in early phases of development.

Besides their direct impact on human health, particles influence the rate of formation of ozone by scattering and absorbing ultraviolet (UV) radiation. UV-absorbing particles can inhibit photochemical reactions and ozone production and UV-scattering particles can accelerate those processes. In some cases, such inhibition and acceleration can result in decreased photolytic rates at the surface but increased rates a few hundred meters aloft (Dickerson et al. 1997). Because particle-UV radiation interactions are not represented in most air-quality models, model applications for ozone and particulate matter may not be realistic assessments of the effects of emission controls.

Other uncertainties in present model formulations include the following:

- Nature of the physical processes that lead to fugitive emissions of particulate matter.
- Rate of mixing and venting of boundary-layer air with the free troposphere and, conversely, the rate at which free-tropospheric air is mixed into the boundary-layer.
- Rate of oxidation of volatile organic compounds and production of condensable products.
- Rate and frequency of SO_2 conversion to sulfate and NO_x to nitric acid and to nitrate in droplets and fogs.
- Rate of interaction of semivolatile species with particle surfaces.
- Rates of wet deposition, including the dependence of these processes on the type of meteorological system of precipitation.
- Dry deposition and chemical interaction of reactive gases with different surfaces (e.g., vegetation and bare soil).
- Subgrid-scale treatment of large point sources, and the rate at which urban plumes of different origin mix within a given region.

Recommended Research

An improved understanding is needed of the chemical and physical processes that determine the size-resolved chemical abundance of particulate matter. To gain that understanding, a well-balanced program will be needed to identify the critical processes. This will require sets of intensive experiments at a few well-chosen sites. The representation within models of the processes operating at each site should be evaluated by comparison of model predictions with observations. The chosen sites should include sites subject to local emissions and long-range transport (e.g., eastern United States), sites representative of regional background conditions and unperturbed by local emissions (e.g., national parks), and sites dominated by local emissions (e.g., the West Coast). By describing how the rates of the chemical and physical processes are governed in each particular location and by determining how the characteristics of each location relate to other regions, the understanding gained at these unique sites may be extended to the full domain of regions that are not in compliance with the NAAQS.

An additional area for investigation is the effect of large-scale meteorological processes, such as aqueous reactions and precipitation scavenging. Innovative research methods will be needed that go beyond the intensive but short-term measurements made for model evaluation, to clude coverage of the processes that determine the long-term average particulate concentration. Models that couple to and make use of numerical weather-prediction tools may be of particular value in this respect.

The effects of uncertainties in model inputs need to be addressed before source-oriented models can be used with confidence. For example, how do uncertainties in the specification of the following exacerbate the uncertainty in predictions?

- Emissions of volatile and semivolatile organic compounds, including biogenic hydrocarbons, ammonia, and primary particles.
- Meteorological processes above the ground.
- Physical descriptions of clouds and fogs.
- Boundary conditions.

Formal methods for uncertainty analysis need to be developed specifically for particle models and applied to refine the definition of model needs and to determine the required accuracy of these model inputs.

PM research studies are under way to advance the state of the science on chemical processes (e.g., secondary organic aerosol formation, thermodynamic equilibrium of organic species) and meteorological processes, but projects on emission characterization (see Research Topic 3), physical processes (e.g., descriptions of clouds and fogs, deposition rates, sand subgrid-scale mixing processes), and uncertainty analysis either have not been undertaken or do not fully address the research needs. In addition, there is little research on the effect of large-scale meteorological processes on long-term annual average fine-particle concentrations.

Scientific Value

Source-oriented models have the potential to embody all that is known about the relevant processes that lead to particle formation in the atmosphere, and, once tested, to be useful in exploring relationships between gas-and particle-phase emissions and ambient levels of particles. These models are needed not only to study urban and regional air-pollution control proposals in advance of their adoption, but also the effects of atmospheric particles on ozone, regional haze, and the earth's radiation balance.

Decisionmaking Value

The ability to relate emissions accurately to ambient concentrations is critical to the optimal design of emission-control strategies to attain the ambient air-quality standards for particulate matter. Credible source-oriented models will help guide decisions on the emission control measures in future air-quality management plans.

Feasibility and Timing

Source-oriented modeling analyses for developing state implementation plans will likely need to be completed prior to the 2005–2008 deadlines. However, to have suitable models in place by the time they are needed, initial model development should be pursued now.

Air-quality models useful for emission-control strategy planning are needed as early as 2003 to meet projected regulatory schedules. Development and testing of those models must begin immediately to meet that schedule, yet during the period of model development and testing, new health-effects research results may help to focus attention on biologically important components of the airborne-particle complex. In the interim, relatively complete air-quality models will have to be developed to describe the size distribution, chemical composition, trace-metal content, acidity, and other likely candidates for a more focused control program. Given the complexity and hence relatively long development times of the source-oriented models with their high science content, a family of less-complex modeling tools (e.g., receptor models) also should be maintained for use in the early stages of control strategy planning (see Research Topic 4b).

In addition to the need for simultaneous development of models at different levels of complexity, EPA's projected regulatory schedule also implies that model-evaluation efforts through regional field studies will need to be conducted simultaneously in several portions of the country. The need to work simultaneously in several regions will challenge the capacity of personnel with the ability to apply complex air-quality models. Managers will need to assess the expertise of their staff, coordinate across regions to determine the models that are most suitable and feasible, and provide training on model applications as needed. The committee's cost estimates reflect the expected costs to be incurred when pursuing model development and testing simultaneously on several fronts.

The comprehensive field experiments and emission inventories required for the application of source-oriented models typically take 5 to 6 years: 2 years to plan and fund, I year for field measurements, another year for data validation and archiving, and one or two years for development of meteorological and air-quality input files and for model evaluation. Thus, major nonattainment areas would need to be identified soon so that the planning for the field experiments can begin. The Northern Front Range Air Quality Study was recently completed (Watson et al. 1998a), and there is an ongoing study in Atlanta (Edgerton et al. 1998). The only upcoming comprehensive field campaigns approaching adequate funding are in central California and the southeastern United States. The California Regional $PM_{10}/PM_{2.5}$ Air Quality Study is scheduled to begin data collection in late 1999 and continue to early 2001. The Regional Ozone/Fine Particle Intensive Field Study in the southeastern United States is planned for the summer of 2000. In addition, a large regional study is being planned for the eastern United States.

Cost

Research is needed to develop a better understanding of the individual chemical and physical processes that govern atmospheric particle formation. Although some research on those processes is being supported, the range of sites to study the processes needs expansion. EPA's $15 million supersites program could serve as the nucleus for such a research effort by providing instrumentation and infrastructure support at five to seven sites. The cost of supporting six institutions to conduct research at the supersites is estimated at $1.7 million per year, beginning in 2000 and extending to 2006. However, the research to be conducted in association with monitoring supersites has not yet been well defined, so uncertainty remains about whether or not these needs will be met.

In addition, integrating the results from theoretical, laboratory, and field studies into comprehensive computer models and analysis and evaluation of the models needs to be carried out continuously, including application of the models to the range of sites and physical and meteorological situations envisioned here. This includes studies of physical processes not now being pursued, such as the formation of clouds and fogs and their effects on particles. It also includes exploration of how the representation of subgrid scale processes affects predictions. Finally, the model application studies must also explore the sensitivity of the applications under different meteorological regimes to uncertainties such as the specification of boundary conditions, emissions inventories, and initial conditions. In addition, continuing research to develop better computer representations of physical and chemical processes needs to be supported. These application studies should be pursued following each of the field studies envisioned here and could involve five to six different modeling groups at up to $350,000 per year for a total cost of perhaps $2 million per year.

The committee also sees the need for development of methods to incorporate the effects of large-scale meteorological processes on annual average particle concentrations through the development of simplified versions of present models and through the development of more realistic larger-scale models that can provide boundary conditions for the detailed models. Some of the additional studies could be pursued if the results of prior field studies were better used. One reason for under use of existing data is the difficulty in accessing them. A central national archive of data and model input files from field-measurement programs would facilitate evaluation of particle models. A scaled-down effort on all these tasks—costing about $2 million—was begun in 1998; about $2.8 million per year is needed from 2000 to 2006.

A major obstacle to the advancement of source-oriented models is the lack of detailed data bases to evaluate predictive capabilities. The costs for year-long field campaigns have ranged from $12 million for the 1987 Southern California Air Quality Study (Lawson 1990) to $27.5 million (including model application and evaluation) for the central California study (Watson et al. 1998b). These costs are high because aircraft, lidars, radar wind profilers, and possibly some customized source testing are needed to characterize air quality and meteorology in time and space. Costs for such efforts in the future can only be partially offset by EPA's supersites program and the planned expansion of the nationwide network of speciation and IMPROVE samplers by 400 sites. The supersites can become the focus of a set of intensive measurement programs to carry out the research outlined above, and other network locations, and perhaps specific additions during special campaigns, can serve to provide larger regional understanding of the chemical and physical state of the atmosphere. In addition, a well-balanced aircraft component is essential to campaigns intended to support model evaluations. The scientific infrastructure in the United States can support one or two comprehensive regional field studies per year. Therefore, in addition to the cost of research, about $20 million from public and private sources will be needed each year from 2001 to 2005 for technical work in support of the evaluation and testing of air-quality models for particulate matter. The results of such work will also be applicable to models for tropospheric ozone.

4b. Receptor-Oriented Models

Receptor-oriented models provide an additional tool to develop effective and efficient strategies to improve human health by improving air quality. These models have been used to identify and quantitatively apportion aerosol mass to sources. However, improved methods are needed because there are limitations in the existing, widely used models. One limitation of existing models used with routine data is that they can have difficulty resolving the contributions of chemically similar source categories that require different control measures, such as gasoline evaporation versus automobile-tailpipe emissions, or road dust versus agricultural and construction activities. A second and more fundamental limitation for fine-particle applications is their inability to handle secondary species.

The currently accepted methods, like CMB or principal components analysis, cannot provide definite identification of the sources of secondary particles such as sulfate, nitrate, or secondary organic materials. The usual result of a CMB analysis is to list sulfate as a source or possibly describe it as "regional sulfate." Similar results are typically obtained through factor analysis.

Three general approaches can be pursued to meet the needs for improved methods. First, additional constituents or properties of the aerosol can be determined and used to identify and apportion sources, enabling much-improved source resolution. In recent years, more intensive analysis of organic compounds in particulate matter has been shown to be an effective way to determine additional sources. Schauer et al. (1996) used a CMB approach to resolve up to nine sources of particulate matter in the Los Angeles area after performing an extensive series of source sampling and ambient sampling coupled with high-resolution gas chromatography and GC/MS techniques. This speciated-hydrocarbon approach produces data on 30–40 compounds that might be present in the source emissions and ambient aerosol. Fujita et al. (1998) applied the speciated-hydrocarbon approach to apportion carbonaceous aerosols in the Northern Front Range area. New analytical methods and identification of additional compounds could provide the ability to identify and apportion additional sources. For example, biological compounds, such as phospholipid fatty acids or DNA, could identify particular crop types being grown on particular soils (Bruns et al. 1998).

Increased resolution can also be provided through examination of individual particles in a sample. Continuous particle-by-particle analysis systems can now qualitatively determine the composition of individual particles and characterize their ambient size distribution, but fully quantitative analysis is still under development. Thus, there is a need for new and improved methods that will provide more detailed characterization of the samples and will thus improve source resolution. However, increased costs are associated with the increased difficulty and sophistication in the analytical methods and related procedures. Therefore, it would be useful if other data-analysis methods were available to use data that can be obtained more easily or are already being obtained routinely for other purposes.

In a second approach, spatial/temporal information can be used to identify potential source locations and emission strengths of the gaseous precursors of secondary particles. This general approach employs a mathematical framework to analyze the values of a single variable measured at a variety of sites at multiple times. Thus, the analysis examines spatial and temporal patterns in the measured variable rather than the interrelationships among different variables. This approach has been used in earlier studies, but generally in a qualitative manner. Recently, efforts have been made to develop factor-analysis methods that yield quantitative apportionment estimates. These methods merit further attention in areas where such widespread sampling has been or will be performed. However, more development, testing, and validation are needed.

Finally, meteorological information in the form of air-parcel-back trajectories can be incorporated into the analysis. Dispersion models describe the transport of the particles from a source to the sampling location. These models can also be used to calculate the trajectories of air sampled at the receptor site backward in time and space to the start of the sampling interval. Various statistical techniques can then be employed to extract patterns of empirical association between the resulting back trajectories and contaminant concentrations in arriving air. Initially, most of these efforts produce qualitative estimates of the importance of various areas on the observed concentrations. Recently, this approach has been extended to yield an apportionment by combining it with the emissions inventory for the area being modeled. Several of these methods can provide quantitative estimates of the contribution of a given area to the concentrations observed at the receptor site. However, these methods have not yet been adequately tested.

Recommended Research

Better mathematical tools are needed to identify patterns in the spatial and temporal variability of PM properties and to relate these to source contributions. These tools must be applicable to data sets containing missing or below-detection-limit values. In addition, the tools must be able to provide solutions that have appropriate constraints. Tested receptor models for secondary particulate matter would be of great value. New models are needed for resolving the components of personal exposure incorporating ambient and indoor sources.

Also needed are new ambient monitoring techniques with the capability of measuring chemical species and particle sizes associated with the inorganic and organic fractions of $PM_{2.5}$ and PM_{10}. To advance exposure and risk assessment, it is particularly necessary to identify and quantify a much larger fraction of airborne PM mass in terms of specific biologically important compounds. Current methods are only able to identify and quantify about one-tenth of the organic material associated with particles. Significant improvements in analytical methods that lead to readily applicable techniques would be an advance in analytical science and provide for major improvements in exposure and risk assessments.

Finally, as part of the evaluation of receptor and source models, studies should be conducted in which both types of models are run and the results intercompared. The reconciliation of the source apportion ments produced by the different model types will help to improve both models because they will help to uncover problems and limitations in the models, their input data, or the interpretation of the results.

Scientific Value

The development and use of advanced receptor models would help to improve understanding of source-receptor relationships and provide critical information complementary to the more advanced source-oriented models.

Decisionmaking Value

Accurate identification of the sources of specific types of ambient particles is critical to the development of effective and efficient air-quality-management strategies focused on biologically important PM components. Receptor-modeling methods for the quantitative apportionment of PM mass and/or specific biologically important species will be important tools to provide to state and local regulatory officials to facilitate the development of state implementation plans.

Feasibility and Timing

Numerical tools can now be used to improve the quality of receptor models. Measurement of the critical organic fraction has improved in recent years with improved chromatographic methods, along with better methods to transfer the output of the chromatograph to the mass spectrometer, but those improvements have not been fully developed for atmospheric particulate species. The resolution and sensitivity of mass spectrometers have also improved, so the necessary basic tools are available.

To develop, evaluate, and improve the models, appropriate air-quality data will be needed. A well-designed monitoring program could help facilitate this effort and could minimize the costs of collecting incremental data for modeling purposes. Because plans for the speciation and supersite monitoring programs are still evolving, it is not yet clear just how EPA's PM-monitoring activities will specifically help the atmospheric-modeling community meet the needs of decisionmakers, and the committee looks forward to further clarification and development of EPA's PM-monitoring programs. The committee urges EPA to increase its efforts to work with the scientific community in finalizing the design of these programs.

Cost

About $1 million per year is needed from 2000 through 2002 for the development of advanced receptor models and related analytical methods development.

RESEARCH TOPIC 5: ASSESSMENT OF HAZARDOUS PARTICULATE-MATTER COMPONENTS

What is the role of physicochemical characteristics of particulate matter in eliciting adverse health effects?

Background

This topic encompasses a broad area of research on the physicochemical and biological characteristics of particulate matter that influence adverse health effects following exposure. This category includes evaluation of particulate characteristics such as chemical composition (including any adsorbed materials) and particle size, development of PM surrogates, and assessment of relevant dose metrics. Research in this area is needed to provide information on whether biological effects are nonspecific or whether they depend upon specific physicochemical parameters of particulates. This evaluation also requires studies of the toxic effects of inhaled particles of various sizes that are chemically, biologically, and immunologically inert to determine if there are generic effects of particles.

The committee's first report recommended that the physicochemical characteristics of particles be considered in the following four specific, but overlapping, categories of research:

- Development and use of PM surrogates for controlled exposures that can mimic daily, seasonal, and regional particle characteristics.
- Assessment of different dose metrics, such as mass, number, surface area, chemical constituents (oxidant activity, organics, and metal content) that relate to health outcomes.
- Evaluation of the role of particle size (e.g., ultrafine versus fine versus coarse-fraction particles) in assessing the results of *in vitro*, whole animal, and controlled human-exposure studies.
- Determination of the role of PM chemistry in toxicological responses.

Update

In response to the committee's recommendation for increased research in this area in its first report (NRC 1998), Congress increased the resources devoted to research on this topic from $4.5 million in the President's proposed budget for Fiscal Year 1999 to $8.2 million in 1999 appropriations, and EPA has proposed $7.9 million for Fiscal Year 2000. There has been an increase in the number of studies that make use of concentrated ambient air particles (CAPs) for real-time exposures of normal and compromised (susceptible) animal models. The particle concentrators are designed to be used in permanent as well as mobile facilities, and they include devices capable of producing size-range-specific concentrated ambient particles. In addition, EPA and other organizations are conducting or planning similar studies in normal and mildly asthmatic human subjects. Several efforts are directed toward developing the capability of providing well-characterized resuspensions of filter samples of particulates for use in toxicological studies involving exposures via inhalation and intratracheal instillation.

EPA and other agencies are sponsoring studies directed toward understanding the potential impact of mass, size, number, and surface area of particles on their toxicity. In the past, many studies at EPA were conducted with resuspended materials instilled directly into the lungs of rodents, but more research at EPA and other organizations is now examining potential dose metrics following inhalation exposure.

New toxicological studies are also being sponsored by organizations other than EPA, such as HEI, the National Institute of Environmental Health Sciences (NIEHS), and the California Air Resources Board to examine differences in toxicological responses to particles of different sizes. A new controlled clinical exposure study in the United Kingdom will use subjects exposed to concentrated air particles and ultrafine diesel particles to assess several biological responses. Several new epidemiological studies will examine the role of particle size on toxicity of particles through the new EPA PM research centers. A major epidemiological study sponsored by EPRI, the Department of Energy (DOE), and several other groups is under way in Atlanta. That study is collecting detailed daily air-quality data for several PM size categories along with PM chemical characterization data and several types of health data.

EPA and other organizations are sponsoring new toxicological and controlled clinical studies to study the effects of various aspects of particulate chemistry on toxicological responses. Those studies will also investigate the potential role of organics in producing adverse health effects.

This research topic area remains a critical area of investigation. The committee recommends that additional inhalation-chamber studies of animals and humans using well-characterized and reproducible particle sizes along with specific gases found in ambient air should be conducted to study the role of physicochemical characteristics in particle toxicity. Studies using concentrated ambient air particles must also take into consideration exposure to gaseous copollutants in evaluation of toxic responses. Regional and seasonal differences in pollutant mixes must also be considered in designing laboratory-generated atmospheres.

Efforts should be undertaken to conduct epidemiological studies of the effects of long-term exposures to particle constituents, including ultrafine particles. Unfortunately, it will be difficult to reconstruct past exposures so that cohorts of exposed subjects can be identified. Further work will be necessary to develop biomarkers that reflect chronic exposure to particulates.

Identifying cohorts in which chemical-species-specific exposures can be explored must be considered a high priority. With the potential for detailed chemical-species identification of particle exposures being developed, interactions of specific particles in well-characterized populations, especially those considered as potentially susceptible, should be explored.

Cohorts that can be followed need to be identified for future epidemiological studies. Populations of adults (healthy and susceptible sub-populations), as well as infants and children, will be needed. Linkage to chemical-speciation sites will need to be considered, along with collections of relevant covariate data. These studies are likely to be multicenter efforts that will need central organization and data collection.

RESEARCH TOPIC 6: DOSIMETRY: DEPOSITION AND FATE OF PARTICLES INTHE RESPIRATORY TRACT

What are the deposition patterns and fate of particles in the respiratory tract of individuals belonging to presumed susceptible subpopulations?

Background

Knowledge of the tissue-specific and cell-specific dose of particulate matter and of PM constituents is a critical link between individual expo sures and health responses. The concept of dose includes the magnitude and rate of deposition on respiratory tract surfaces; the clearance, dissolution, and translocation of particulate matter from various sites; and the bioavailability of PM-borne toxic compounds. This information not only is critical to understanding exposure-dose-response relationships for health risks, but also to extrapolating the relationships between different types of human subjects and between experimental animals and humans.

The delivery of particle dose to the respiratory tract is not uniform; some regions and localized areas receive much greater doses than others. Work to date in this area has shown that local doses can be increased even further by the presence of respiratory disease.

Mathematical models have been developed for predicting the regional deposition of particles in the respiratory tract. Although the models are available for making useful predictions of the deposition of particles of various sizes in normal adult human airways, there is a basic need for experimental measurements to refine the models and to validate them through studies of deposition in living subjects.

The committee recommended that the following specific research tasks be undertaken with respect to deposition patterns and fate of particles in the respiratory tract:

- Develop a quantitative description of representative lung morphometry and breathing patterns of potentially susceptible sub-populations (especially subjects with lung diseases, elderly subjects, and children).
- Obtain a better understanding of particle deposition patterns within the respiratory tracts of susceptible subpopulations as a function of particle size, hygroscopicity, and breathing rate over the entire range of particle sizes.
- Develop and refine mathematical models for predicting regional and local deposition in the respiratory tracts of subjects with lung disease, elderly subjects, and children for particle sizes of interest. To the extent possible, models should be tested using experimentally collected deposition data.

Improve understanding of clearance and other defense mechanisms in healthy and susceptible populations, including understanding of phagocyte function, translocation to tissue and extrapulmonary compartments, and the bioavailability of particle-borne constituents.

Update

In addition to the research needs described in the committee's first report, more information is needed on particle dosimetry in different species of laboratory animals to provide a stronger foundation for extrapolation modeling. In particular, improved understanding of the regional deposition and retention of different particle types and sizes in normal and respiratory-disease-compromised animals would aid in the development of extrapolation models aimed at predicting dosimetry in humans with respiratory diseases.

Some of the previously mentioned research needs are being addressed by ongoing or planned research sponsored by EPA and other organizations, but it is not apparent that all of the research needs are being met. A portion of continuing and new research efforts sponsored by EPA, the HEI, DOE, and other organizations is focused on dosimetric issues. Although all of the previously described research needs are important, it is important to obtain a better understanding of the dosimetry of particulates in lungs of susceptible subpopulations. Consequently, the first two of the above four research areas should be given highest priority.

In its first report, the committee noted that dosimetry research needs could be met by approximately 4 years of adequate funding. It was also noted that this work did not depend on the products of other research areas or the establishment of monitoring programs and thus, could begin as soon as funding could be allocated. The committee recommends that EPA increase funding for dosimetric research during the early years of the program, so that these information gaps can be filled and the information can serve as a foundation for research under other topics.

RESEARCH TOPIC 7: COMBINED EFFECTS OF PARTICULATE MATTER AND GASEOUSPOLLUTANTS

How can the effects of particulate matter be disentangled from the effects of other pollutants? How can the effects of long-term exposure to particulate matter and other pollutants be better understood?

Background

The Clean Air Act requires the administrator of EPA to set standards for particulate matter and other criteria pollutants to protect the public health with "an adequate margin of safety." The act implicitly assumes that regulation of individual pollutant concentrations will protect the public from adverse effects. Air pollution in virtually all locations, however, is a complex mixture; the potential for additivity, synergism, and other interactions among the components of the mixture may produce effects that would not be anticipated from predictions based on understanding of the effects of the individual criteria pollutants. Thus, research must also be sustained on other components of the complex pollutant mixtures.

In its first report, the committee observed that to characterize the health risks associated with exposure to particulate matter it is important to consider the effects of combined exposures to particulates and other copollutants. In addition to particulates, ambient air includes gaseous pollutants, including sulfur oxides, nitrogen oxide, carbon monoxide, and ozone, as well as organic compounds. These copollutants, which are often highly correlated with particulate matter, can also present health risks, or can modify the effects of particulate matter as a consequence of combined exposures. Although it is important to attempt to understand the health effects of particulates and to differentiate them from the effects of copollutants, it is critical to understand the modifying effects of copollutants on the health impacts of particulate matter. This is particularly necessary in regard to long-term exposure to particulate matter in the presence of other pollutants.

The committee noted in its first report that toxicological and epidemiological studies can be used to obtain answers to questions relating to such complex toxicological interactions. Toxicological studies provide opportunities to understand interactions between particulates and copollutants through controlled experiments. Most epidemiological studies involving analysis of multiple pollutants have focused on the effects of short-term exposures. However, in some studies of long-term exposure to particulate matter, excess mortality has been reported. The committee recommended that further epidemiological investigations of the effects of long-term exposure to particulate matter are needed and that such studies be designed to evaluate also the influence of long-term exposures to gaseous copollutants. Such toxicological and epidemiological investigations would clarify the effects of exposure to particulate matter in the presence of concomitant exposures to other gaseous copollutants.

While supporting further epidemiological investigations of the effects of long-term exposures to ambient particulate matter, the committee recommended that exposure-monitoring programs are needed to adequately characterize population exposures to particulates, and that these programs should be in place before or contemporaneously with the initiation of new epidemiological studies. Thus, in strengthening the existing air-pollution monitoring programs in the United States, consideration needs to be given to the need for developing adequate exposure data for future long-term epidemiological investigations of particulates and copollutants.

Research Topic 7 addresses the estimation of the effects of particulate matter in the context of the effects of other pollutants. Statistical analyses can be carried out using observational data for this purpose. Experiments can also be designed that provide information concerning the independent contributions of individual pollutants to toxicity. However, the statistical analyses of observational data and the evidence from experiments may not accurately reflect the biological processes that lead to injury when complex mixtures are inhaled. The committee offers this cautionary reminder and also recommends that efforts be continued to better understand how mixtures exert their adverse effects. Research Topic 10 includes research to investigate measurement errors, which can be particularly important in statistical analyses that include several pollutants with different measurement errors.

Update

In response to the committee's first report, which recommended greatly expanded work in this area, EPA and Congress increased the resources devoted to this research from $0.8 million in the President's proposed budget for Fiscal Year 1999 to $7.4 million in 1999 appropriations, and EPA has proposed $8.5 million in Fiscal Year 2000 (see Table 1.4). The committee supports and welcomes these decisions.

Current studies are investigating toxicological interactions of particles and pollutant gases as part of EPA's extramural Science to Achieve Results (STAR) research grants program. In addition, the National Environmental Respiratory Center has been created at the Lovelace Respiratory Research Institute as part of a long-term program to better understand the respiratory health effects of mixtures of air contaminants and the relative roles of individual constituents in producing health effects from exposure to pollutant mixtures. The work of this center will include evaluation of the relative roles of particulates and copollutant gases and vapors. The center is jointly funded by EPA and other sponsors. In addition, several studies, including the recently funded reanalysis of the Six City and American Cancer Society studies by HEI will also provide an opportunity to explore possible modifying effects of copollutants on the effects seen from particulate exposures.

The success of future studies on the effects of long-term exposures to particulates will depend heavily on the adequacy of exposure data for particulates and other copollutants. In developing its plans to expand the existing PM air-quality-monitoring programs, EPA will need to take into consideration exposure data needs for epidemiological studies as well as for ascertaining compliance with the NAAQS. The current lack of an adequate, coordinated effort by federal research programs to develop and track new cohorts or to enhance existing cohorts threatens to undermine the planning and implementation of new long-term studies in conjunction with the enhanced monitoring.

RESEARCH TOPIC 8: SUSCEPTIBLE SUBPOPULATIONS

What subpopulations are at increased risk of adverse health outcomes from particulate matter?

Background

As discussed in the committee's first report, epidemiological data suggests that some human subpopulations are especially susceptible to inhaled particulate matter. These subpopulations include persons with cardiopulmonary disease or asthma, as well as the elderly, infants, and children. Other susceptible subpopulations, as well as personal and environmental factors that affect susceptibility, are largely unknown. The likelihood of adverse responses to particles depends upon the degree of exposure and individual characteristics that determine the susceptibility of exposed persons. Susceptibility can relate to a number of factors that vary among individuals, including particle dosimetry (deposition, clearance, and retention); individual characteristics, such as age, sex, prior disease history, and genetic characteristics (e.g., allergic responses); personal habits, such as smoking; and environmental factors, such as exposures to biological or chemical agents.

The behavior and activity patterns of susceptible subpopulations may bring them into contact with pollutant mixtures including particulates, that are different from the exposures of the general population. In addition, individual variations in deposition, retention, and clearance rates may alter a subpopulation's biologically available and effective doses and responses. The lack of information on these important factors impedes the development and validation of effective models for exposure assessment.

The committee recommended studies to determine the importance of short-term, peak, cumulative, and long-term PM exposures on mortality, premature mortality, and acute and chronic adverse health effects. These studies were recommended to include

- The development of appropriate animal models.
- Controlled human-exposure studies.

- Epidemiological studies in appropriately selected susceptible subpopulations.

Update

EPA and several other organizations are sponsoring studies to examine susceptibility factors, particularly pre-existing cardiopulmonary disease. Several studies are developing or using animal models of disease (e.g., asthma, chronic obstructive pulmonary disease, or cardiovascular disease). Controlled human-exposure studies that use concentrated ambient particulates as well as surrogate particles are also under way or planned; these studies will involve healthy volunteers as well as susceptible individuals with asthma and chronic lung disease. However, ethical considerations preclude studies involving extremely high exposures or individuals with severe diseases. Although *in vitro* studies with cell lines from normal and susceptible subpopulations are being conducted, the extrapolation of findings from *in vitro* studies to humans is difficult. However, such *in vitro* studies may aid in understanding the mechanisms, if dosimetric concerns can be addressed.

Recent studies (Liao et al. 1999; Tolbert et al. in press) have contributed to knowledge about susceptible subpopulations (e.g., the elderly), but much more knowledge is needed to support decisionmaking for PM standards. Additional studies are planned or under way for various parts of the United States that will assess cardiovascular outcomes in individuals believed to be at excess risk.

There is no centralized research inventory of studies of susceptible subpopulations, and the committee is not aware of any coordinated plan by which current and expected studies can be assessed in the context of the research recommendations in the committee's first report. Consequently, it is difficult to determine what research is still needed. For example, it is not clear from available study descriptions how pregnant women, minority, ethnic, or economically disadvantaged subpopulations will be studied. Similarly, available descriptions of the studies do not indicate whether peak levels of particles or ambient biological agents will be investigated.

The committee is concerned that current research efforts in this area may be too limited to be effective in guiding and monitoring research on the effects of particulate matter in susceptible subpopulations. The committee recommends that EPA explore greater collaboration with other federal agencies and private research organizations to leverage resources and maximize ongoing research opportunities. EPA's work must take into account opportunities offered by such major studies as the Women's Health Initiative, the EPRI Veterans' Study, Harvard studies of medical personnel, inner-city asthma studies in various areas, and studies by large health-management organizations (including health maintenance organizations). A strategy containing short-and long-term components of the PM research program is needed to ensure the effective identification of health effects among susceptible subpopulations as well as general population cohorts, and to identify the most appropriate and cost-effective means to address the effects. The com mittee recommends that the strategy include

- Updating the inventory of large-cohort, health-research studies with relevant co-variables.
- Identifying what health outcomes need to be addressed.
- Identifying and prioritizing what susceptible subpopulations still need to be studied.
- Identifying what research needs, as discussed above and in the committee's first report, will not be addressed by ongoing studies.
- Identifying potential collaborators with access to cohorts in selected cities (e.g., Los Angeles and Atlanta).

RESEARCH TOPIC 9: MECHANISMS OF INJURY

What are the underlying mechanisms (local pulmonary and systemic) that can explain the epidemiological findings of mortality/morbidity associated with exposure to ambient particulate matter?

Background

As discussed in the committee's first report, this is another critical area of research. The value of epidemiological studies will be greatly enhanced if results obtained in controlled exposure studies can provide plausible explanations of underlying biological mechanisms for health effects. This research is needed to provide an understanding of local pulmonary and systemic responses. Although research in several other areas will also contribute to elucidation of pathophysiological mechanisms of particle-induced injuries (see research topics 5–8), this section focuses on the use of clinical, animal, and *in vitro* models to evaluate such mechanisms.

Clinical studies are controlled experimental exposures of humans to a substance. When possible, such studies with laboratory-generated surrogate particles or concentrated ambient air particles are an approach of choice. The use of human subjects avoids the need to extrapolate from other species. Human-exposure studies use laboratory atmospheric conditions that can be relevant for ambient pollutant concentrations, and they document physiological responses resulting from exposure that can often be linked to health effects. In these studies, highly controlled environments or well-characterized CAPS can be used to identify health responses to individual pollutants and to characterize exposure-response relationships. In addition, a controlled environment provides the opportunity to examine toxicological interactions among pollutants or with other variables, such as exercise.

In laboratory-animal studies, animal models are used as surrogates for humans. The necessity and urgency of developing and validating appropriate animal models of susceptible human subpopulations remains a critical area of research. The use of such animal models is essential for characterizing potential adverse effects of inhaled particles, as well as for determining specific mechanisms that seem to be operating only in the susceptible organism. Among the different animal models that mimic human diseases, the usefulness of transgenic animals should be evaluated to investigate specific mechanistic hypotheses.

In vitro studies can be used to evaluate some specific mechanistic hypotheses related to health effects from exposure to particles. As reviewed in the committee's first report, the use of relevant target cells, as well as the use of particle doses comparable to exposure scenarios encountered *in vivo*, is crucial. Although initially higher dose levels may have to be tested, mechanisms that operate at high-particulate doses may be irrelevant for low doses. For example, it is known that high exposure concentrations to low-toxicity particles lead to particle overload, impaired clearance, and specific lesions, such as fibrosis and tumors not seen at lower concentrations. Thus, extrapolation from *in vitro* data and mechanisms elucidated from the use of high doses may be flawed unless it can be shown that health responses observed following exposure to low doses do indeed follow the same mechanistic pathways. It is also critical that all cell and tissue models be validated; the issue of whether responses observed in these *in vitro* models reflect those that would occur *in vivo* is also critical.

Update

In response to the committee's first report, which recommended increased work in this research area, EPA and Congress increased the resources devoted to this research from $4.3 million in the President's budget for Fiscal Year 1999 to $8.3 million in 1999 appropriations, and EPA has proposed $6.8 million in Fiscal Year 2000 (see Table 1.4).

To evaluate particle-induced effects, clinical studies are being conducted or planned in healthy volunteers and individuals with underlying cardiopulmonary diseases, such as asthma, chronic obstructive pulmonary disease, and angina. A variety of techniques to assess airway inflammation will be used, including bronchoalveolar lavage, sputum induction, and measurement of nitric oxide in exhaled air, as well as assessment of systemic effects by measurement of bloodborne biomarkers of effects and exposure. Assessment of cardiac rhythm and the coagulation cascade will also be studied. These studies will provide important information on early physiological responses from exposures to particles and will potentially provide important information on mechanisms of injury related to acute and chronic health effects.

Emphasis has increased on using animal models of diseases that are thought likely to increase human susceptibility to inhaled particulate matter. There is now a broad recognition that research based solely on the use of young, healthy animals is not likely to lead to an adequate understanding of health risks to susceptible human subpopulations. Several genetic and experimentally induced laboratory models of emphysema, asthma, inflammation, infection, aging, and cardiovascular disease are now being used in PM research. Animals are also being used to explore the influence of age on susceptibility. Because all existing animal models have limitations in their ability to fully mimic human conditions, continued effort is needed to make adequate progress in developing and evaluating animal models of the full range of human conditions of interest.

The development of advanced molecular biology techniques makes it possible to employ methods such as *in vitro* transfection models for evaluating specific mechanisms of particle-cell interactions. Also useful for evaluating specific mechanisms are *ex vivo* studies in which specific cells of the respiratory tract are isolated after *in vivo* exposures of animals, and then subsequent *in vitro* studies are performed.

Careful consideration must be given to the extent to which the animal models represent the human conditions being modeled. For example, interspecies differences in dose to critical tissues, organ-level physiology, and genetics must be considered when judging the degree to which the animal models mimic human doses and responses. Few, if any, animal models accurately represent all features of a human disease, so consideration must be given to determine which features of the disease are modeled by the animal-test systems.

Understanding mechanisms of toxicity remains a high-priority research area, because the primary goal is to provide biological plausibility for the epidemiological findings related to ambient particulate matter. Although the overall funding planned by EPA in this area approaches the recommendations of the committee's first report, it is not clear to the committee how the funds will be allocated among clinical, animal, and *in vitro* studies.

As discussed under Research Topic 3 in the committee's first report, research is needed to develop advanced analytical methods to monitor responses to toxic components of particulate matter. Such research will involve the use of animal models and human subjects. In its first report, the committee estimated the cost of this research at $1.5 million per year for 3 years beginning in 2001. However, the committee has decided to move that research from Research Topic 3 to Subtopic 9c to consolidate similar activities together.

RESEARCH TOPIC 10: ANALYSIS AND MEASUREMENT

To what extent does the choice of statistical methods in the analysis of data from epidemiological studies influence estimates of health risks from exposures to particulate matter? *Can existing methods be improved? What is the effect of measurement error and misclassification on estimates of the association between air pollution and health*?

Background

In its first report, the committee noted that a persistent source of the uncertainty associated with epidemiological studies on the health effects of particulate matter can be tied to questions about the statistical methods used to analyze the data and to the inherent errors associated with variables in the analyses. Several alternative methods have been used in these analyses, and the influence of those methods on the results and conclusions have not been fully understood. In addition, the observational data used in the studies are subject to measurement error.

The influence of any methodological approach on the results of an analysis must be understood. There is also value in determining whether results and conclusions are robust compared with alternative methods. In addition, measurement error can have extensive influence on the results of an analysis. It can bias the estimates of association and dose-response between pollution and health end points; the extent of such bias needs to be assessed and methods need to be found to correct for it.

Update

The above issues will be amplified in new studies that consider exposures to many pollutants. The inclusion of many pollutants, some of which are correlated with each other, are creating a situation in which it will be difficult to determine the specific pollutants most highly associated with a health outcome. Differences in measurement error compound the difficulties introduced by this situation.

As we achieve greater understanding of the biological basis of health effects of particulates, it will be important to factor this understanding into models and statistical analyses. The current generation of models includes very flexible and powerful tools that can incorporate complex relationships between variables. The challenge is to articulate these relationships and then incorporate them in data analyses.

In epidemiological studies of the relationship between particles and health, an individual's exposure to particles is estimated most often by measurements taken at an ambient monitor. Rarely are measurements of personal exposure available. The difference between actual exposures and measured ambient-air concentrations can be considered as measurement error. Measurement error for air-pollution exposure has three significant components: instrument error (the accuracy and precision of the monitoring instrument), error resulting from nonrepresentativeness of a monitoring site (reflected by spatial variability of the pollutant measured), and differences between the average personal exposure of a pollutant and the monitored level.

Several efforts are under way to characterize the difference between personal exposures and ambient monitored levels of pollution variables (see Research Topic 1). Those efforts are addressing several populations in several regions. Data are especially needed on human subpopulations thought to be susceptible to air pollution. The distribution of differences between personal exposures and monitored ambient levels must be described. As the number of variables increase, this task will become more difficult. Differences in the underlying attributes of measurement error across population subgroups should be characterized. Differences in error distribution across subgroups could affect causal interpretations.

For most of the criteria pollutants, data are available to characterize spatial variability—another source of measurement error. However, for many particulate subspecies that we are only beginning to measure, these data are not available. For other species, some efforts to characterize the variability are under way. Errors associated with instrument accuracy and precision also need to be characterized. This could be problematic for some older measurements that are based upon measurement instruments and technologies no longer used.

Research is under way to characterize the consequences of measurement error. Some of these efforts have focused upon measurement errors with very specific properties. The measurement error is assumed to be random (independent of the true measurement), and the errors are assumed to be independent and identically distributed with a symmetric distribution.

Recent research efforts have applied statistical methods to consider multiple pollutants in the same analysis and have examined the sensitivity of model results to assumptions made in times-series models. In addition, two workshops have been held to address these issues. HEI held a workshop on measurement error, and EPA convened a workshop to discuss broad methodological issues.

In addition, methods are being developed and applied to estimate the extent to which the timing of death may be advanced by pollution exposure ("mortality displacement" and "harvesting"). Methods (metaanalysis and hierarchical analysis) are also being studied to combine the results from several similar studies and to determine when such methods are appropriate.

Several methodological issues need to be addressed further. Systematic investigations of alternative methods and models would provide greater insights on the robustness of results. Alternative valid methods should be systematically applied to a few data sets to indicate the potential sensitivity of results to alternative methods. Data must be collected to ensure that we can adequately characterize the nature and distribution of significant errors for independent variables used in statistical models and that data on the errors are used to make adjustments. Studies with detailed environmental data (e.g., the supersites program) present additional methodological challenges. Finally, as biological understanding improves on the relationships between pollution and health, models must incorporate this understanding.

THE UPDATED RESEARCH PORTFOLIO

As discussed earlier, the committee is continuing to evaluate PM research needs and accordingly to update its research investment portfolio (see Table 3.1). Specifically, the research activities and resource estimates for research topics 2, 3, 4, and 9 have been revised since the first report. Over the 11-year span of the updated portfolio, these revisions increase the total estimated cost of the research from $357.1 million to $369.9 million, increasing the average from $32.5 million to $33.6 million per year.

Research Topic 2 has been divided into two subtopics to distinguish between exposure methods development (Subtopic 2a) and exposure studies (Subtopic 2b).

In the first report, Research Topic 3 contained three subtopics that addressed the development of advanced mathematical, modeling, and monitoring tools to represent source-receptor relationships more accurately. Research Topic 4 addressed the research efforts needed to apply these methods and models to link biologically important components of particulate matter to their sources and to efficient air-quality management. In updating and refining its research portfolio, the committee has reconfigured the activities in research topics 3 and 4 and expanded some of the resource estimates to cover the implementation-related research and data collection that are not expected to be conducted by regulatory program efforts.

Research Topic 3 has no subtopics in the revised portfolio and is focused on research and development for methods to characterize emission sources. These activities are estimated to cost $2.5 million per year for 4 years. However, that amount does not include testing of the most important source types because that activity is viewed as part of the ongoing source surveillance program needed for implementation of the regulatory program. Such testing is represented in Table 3.2.

TABLE 3.1 The Committee's Updated Research Investment Portfolio for Fiscal Year 2000-2010: Timing and Estimated Costs* ($ million/year in 1998 dollars) of Recommended Research on Particulate Matter

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
SOURCE/CONCENTRATION/EXPOSURE											
1. Outdoor vs. human exposure	3.0										
2. Exposure to toxic PM components											
2a. Methods	1.0										
2b. Studies		4.0	4.0	4.0	4.0	4.0					
3. Emission sources	2.5	2.5	2.5	2.5							
4. Models											
4a. Source oriented**	4.5	4.5	4.5	4.5	4.5	4.5	4.5				
4b. Receptor oriented	1.0	1.0	1.0								
EXPOSURE/DOSE-RESPONSE											
5. Assessment of hazardous PM components											
5a. Toxicological and clinical studies	8.0	8.0	8.0								
5b. Epidemiology	1.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
6. Dosimetry	1.5	1.5									
7. Effects of PM and copollutants											
7a. Copollutants (toxicology)	4.0	4.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
7b. Copollutants/long term (epidemiology)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	3.0	3.0
8. Susceptible subpopulations	3.0	3.0	3.0	3.0	3.0	3.0					
9. Toxicity mechanisms											
9a. Animal models	3.0	3.0	3.0	3.0							
9b. *In vitro* studies	3.0	3.0	3.0	3.0							
9c. Human clinical	3.5	3.5	3.5	3.5							
ANALYSIS AND MEASUREMENT											
10a. Statistical analysis	1.0	1.0	1.0	1.0							
10b. Measurement error	1.5	3.0	2.0	2.0							
SUBTOTALS ($ MILLION PER YEAR)	47.5	54.0	51.5	42.5	28.5	28.5	21.5	17.0	17.0	14.0	14.0
RESEARCH MANAGEMENT* (ESTIMATED AT 10%)**	4.8	5.4	5.2	4.3	2.9	2.9	2.2	1.7	1.7	1.4	1.4
TOTALS ($ MILLION PER YEAR)	52.3	59.4	56.7	46.8	31.4	31.4	23.7	18.7	18.7	15.4	15.4

* The committee's rough but informed collective-judgment cost estimates for the highest-priority research activities recommended in this report. See Chapter 3 of this report and Chapter 4 of NRC, 1998 for explanations. These estimates should *not* be interpreted as a recommended total particulate-matter research budget for EPA or the nation, for reasons explained in NRC 1998.

** These estimates are in addition to costs for EPA's supersite program and expansion of the nationwide speciation network, as well as likely expenditures by states, local agencies, and industries for source-emissions inventories and field-measurement campaigns in support of model evaluation studies (see Table 3.2).

***Research management includes research planning, budgeting, oversight, review, and dissemination, cumulatively estimated by the committee at 10% of project costs.

TABLE 3.2 The Committee's Technical Support Estimates: Timing and Estimated Costsa ($ million/year in 1998 dollars) of additional technical work needed for implementation of emissions control programs for airborne particles

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
ACTIVITY											
1. Source testing by regulatory programs			**5.0**	**5.0**	**5.0**	**5.0**	**5.0**				
2. Compilation of interim PM emission inventory	**1.0**	**1.0**	**1.0**	**1.0**							
3. Compilation of PM emission inventory based on results of new source information							**1.0**	**1.0**	**1.0**		
4. Field studies in support of air quality model evaluation and testing*		**20.0**	**20.0**	**20.0**	**20.0**	**20.0**					
TOTALS ($ MILLION PER YEAR)	**1.0**	**21.0**	**26.0**	**26.0**	**25.0**	**25.0**	**6.0**	**1.0**	**1.0**		

* Technical support expenditures by all public and private sponsoring organizations.

In this report, Research Topic 4 has been divided into Subtopic 4a, which addresses the development and evaluation of source-oriented models, and Subtopic 4b, which addresses receptor-oriented models. Because EPA monitoring is not expected to provide adequate data for model evaluation, the committee has increased its resource estimate for source-oriented models from the original estimate in its first report. Subtopic 4b shows the same amount of resources for receptor-oriented model development that was presented in Research Topic 3 of the first report.

Research Topic 9 retains the three subtopics from the first report. However, Subtopic 9c ("Human Clinical") was expanded by reallocating, from Research Topic 3 of the first report, $1.5 million per year for 3 years beginning in 2001 for the development of advanced analytic methods for monitoring biological responses to toxic components of particulate matter.

It is important to recognize that many parts of the research effort will continue to depend heavily upon data developed in technical programs maintained by the government in areas that fall outside the scope of the research activities recommended by the committee. Examples of such activities are testing of emissions sources, compilation of emissions inventories, and much of the collection of ambient data to support testing and evaluation of air-quality models. These technical programs may be carried out by government regulatory or research programs at the federal, state, or local level, or by nongovernmental organizations (see Table 3.2).

REFERENCES

Bruns, MA, K.J. Gram, K.M. Scow, and T. VanCuren. 1998. Biological markers to characterize potential sources of soil-derived particulate matter. Paper 98-A994. Air and Waste Management Association 1998 Annual Meeting. Pittburgh, PA.

Chow, J.C., J.G. Watson, J.E. Houck, L.C. Pritchett, C.F. Rogers, C.A. Frazier, R.T. Egami, and B.M. Ball. 1994. A laboratory resuspension chamber to measure fugitive dust size distributions and chemical compositions. Atmos. Environ. 28(21):3463–3481.

Clayton, C.A., R.L. Perritt, E.D. Pellizzari, K.W. Thomas, R.W. Whitmore, L.A. Wallace, H. Ozkaynak, and J.D. Spengler. 1993. Particle Total Exposure Assessment Methodology (PTEAM) study: distributions of aerosol and elemental concentrations in personal, indoor, and outdoor air samples in a southern California community. J. Expo. Anal. Environ. Epidemiol. 3(2):227–250.

Dickerson, R.R., S. Kondragunta, G. Stenchikov, K.L. Civerolo, B.G. Doddridge, and B.N. Holben. 1997. The impact of aerosols on solar ultraviolet radiation and photochemical smog. Science 278(5339):827–830.

Dolislager, L.J., and N. Motabelli. In press. Characterization of particulate matter in California. J. Air Waste Manage. Assoc.

Edgerton, E., B. Hartsell, J. Jansen, P. Saxena, and R. Wyzga. 1998. State-of-the-Art Time Series Epidemiology-Pollution Study 1. Air Quality Measurements. EPRI, Palo Alto, CA.

EPA (U.S. Environmental Protection Agency). 1985. Compilation of Air Pollutant Emission Factors, 4th ed.-Volume II: Mobile Sources-AP-42 and Supplement A and Appendices A to K. U.S. Environmental Protection Agency, Ann Arbor, MI.

EPA (U.S. Environmental Protection Agency). 1995. Compilation of Air Pollutant Emission Factors, 5th ed.-Volume I: Stationary and Area Sources-AP-42 and Supplements A to E. EPA450AP425ED. U.S. Environmental Protection Agency, Research Triangle Park, N.C.

EPA (U.S. Environmental Protection Agency). 1997. National Ambient Air Quality Standards for Particulate Matter-Final Rule. Fed. Regist. 62(138): 38651–38760.

EPA (U.S. Environmental Protection Agency). 1999. Airborne Particulate Matter Research Strategy. EPA/600/R-99/045. U.S. Environmental Protection Agency, Research Triangle Park, NC.

Finlayson-Pitts, B.J., and J.N. Pitts. 1986. Atmospheric Chemistry: Fundamental and Experimental Techniques. New York: Wiley.

Fujita, E., J.G. Watson, J.C. Chow, N. Robinson, L. Richards, and N. Kumar. 1998. Northern Front Range Air Quality Study-Volume C: Source Apportionment and Simulation Methods and Evaluation. Prepared for Colorado State University, Fort Collins, CO., and EPRI, Palo Alto, CA., by Desert Research Institute, Reno, NV. June 30, 1998.

Hildemann, L.M., G.R. Markowski, M.C. Jones, and G.R. Cass. 1991. Submicrometer aerosol mass distributions of emissions from boilers, fireplaces, automobiles, diesel trucks, and meat-cooking operations. Aerosol Sci. Technol. 14(1):138–152.

Koutrakis, P., S.L.K. Briggs, and B.P. Leaderer. 1992. Source apportionment of indoor aerosols in Suffolk and Onondaga Counties, New York. Environ. Sci. Technol. 26(3):521–527.

Lawson, D.R. 1990. The Southern California Air Quality Study. J. Air Waste Manage. Assoc. 40 (2):156–165.

Liao, D., J. Creason, C. Shy, R. Williams, R. Watts, and R. Zweidinger. 1999. Daily variation of particulate air pollution and poor cardiac autonomic control in the elderly. Environ. Health Perspect. 107(7):521–525.

Lioy, P.J. 1990. Assessing total human exposure to contaminants. Environ. Sci. Technol. 24(7):938–945.

Lioy, P.J., J.M. Waldman, T. Buckley, J. Butler, and C. Pietarinen. 1990. The personal, indoor, and outdoor concentrations of PM_{10} measured in an industrial community during the winter. Atmos. Environ. Part B, Urban Atmos. 24(1):57–66.

NRC (National Research Council). 1983. Risk Assessment in the Federal Government: Managing the Process. Washington, D.C.: National Academy Press.

NRC (National Research Council). 1991. Human Exposure Assessment for

Airborne Pollutants: Advances and Opportunites. Washington, D.C.: National Academy Press.

NRC (National Research Council). 1993. Protecting Visibility in National Parks and Wilderness Areas. Washington, D.C.: National Academy Press.

NRC (National Research Council). 1994. Science and Judgment in Risk Assessment. Washington, D.C.: National Academy Press.

NRC (National Research Council). 1998. Research Priorities for Airborne Particulate Matter. I. Immediate Priorities and a Long-Range Research Portfolio. Washington, D.C.: National Academy Press.

Rogge, W.F., L.M. Hildemann, M.A. Mazurek, G.R. Cass, and B.R.T. Simoneit. 1997. Sources of fine organic aerosol. 8. Boilers burning no. 2 distillate fuel oil. Environ. Sci. Technol. 31 (10):2731–2737.

Saxena, P., and L.M. Hildemann. 1996. Water-soluble organics in atmospheric particles: a critical review of the literature and application of thermodynamics to identify candidate compounds. J. Atmos. Chem. 24(1):57–109.

Saxena, P., A.B. Hudischewsky, C. Seigneur, and J.H. Seinfeld. 1986. A comparative study of equilibrium approaches to the chemical characterization of secondary aerosols. Atmos. Environ. 20:1471–1483.

Schauer, J.J., W.F. Rogge, L.M. Hildemann, M.A. Mazurek, and G.R. Cass. 1996. Source apportionment of airborne particulate matter using organic compounds as tracers. Atmos. Environ. 30(22):3837–3855.

Seigneur, C., P. Pai, J.-L. Louis, P.K. Hopke, and D. Grosjean. 1997. Review of Air Quality Models for Particulate Matter. Document CP-015-97-1b. Publication Number 4669. Washington, D.C.: American Petroleum Institute.

Sexton, K., S.G. Selevan, D.K. Wagener, and.: A. Lybarger. 1992. Estimating human exposures to environmental pollutants: availability and utility of existing databases. Arch. Environ. Health 47(6):398–407.

Thomas, K.W., E.D. Pellizzari, C.A. Clayton, D.A. Whitaker, R.C. Shores, J. Spengler, H. Ozkaynak, S.E. Froehlich, and L.A. Wallace. 1993. Particle Total Exposure Assessment Methodology (PTEAM) 1990 study: Method performance and data quality for personal, indoor, and outdoor monitoring. J. Expo. Anal. Environ. Epidemiol. 3(2):203–26.

Tolbert, P.E., J.A. Mulholland, D.L. Macintosh, F. Xu, D. Daniels, O.J. Devine, B.P. Carlin, M. Klein, J. Dorley, A.J. Butler, D.F. Nordenberg, H. Frumkin, P.B. Ryan, and M.C. White. In press. Air quality and pediatric emergency room visits for asthma in Atlanta. Am. J. Epidemiol.

Watson, J.G., E. Fujita, J.C. Chow, B. Zielinska, L. Richards, W. Neff, and D.

Dietrich. 1998a. Northern Front Range Air Quality Study Final Report. Prepared for Colorado State University, Fort Collins, CO., and EPRI, Palo Alto, CA., by Desert Research Institute, Reno, NV. June 30, 1998.

Watson, J.G., D.W. DuBois, R. DeMandel, A. Kaduwela, K. Magliano, C. McDade, P.K. Mueller, A. Ranzieri, P.M. Roth, and S. Tanrikulu. 1998b. Aerometric Monitoring Program Plan for the California Regional PM2.5/ PM10 Air Quality Study. Prepared for California Regional PM10/PM2.5 Air Quality Study Technical Committee, Sacramento, CA., by Desert Research Institute, Reno, NV. December 20,1998.

Winner, D.A., and G.R. Cass. 1999. Modeling the long-term frequency distribution of regional ozone concentrations. Atmos. Environ. 33(3):431–451.

Appendix A

BIOGRAPHICAL INFORMATION ON THE COMMITTEE ON RESEARCHPRIORITIES FOR AIRBORNE PARTICULATE MATTER

Jonathan Samet (*Chair*), Johns Hopkins University, Baltimore, Maryland.

Jonathan Samet is professor and chairman of the Department of Epidemiology at the Johns Hopkins University School of Hygiene and Public Health. Dr. Samet earned his M.D. from the University of Rochester School of Medicine and Dentistry and an M.S. in Epidemiology from the Harvard School of Public Health. He is board-certified in internal medicine and the subspecialty of pulmonary disease. He was formerly professor and chief of the pulmonary and critical care division in the Department of Medicine at the University of New Mexico School of Medicine. He is past-president of the Society for Epidemiologic Research. He has served on the EPA's Science Advisory Board. He is currently on the Board of Overseers and Board of Editors for the *American Journal of Epidemiology*. Dr. Samet was awarded the Surgeon General's Medallion in 1990. He was elected to the NAS Institute of Medicine in 1997 and currently serves as chairman of the present committee. He also served recently as chairman of the NRC Committee on Health Risks of Exposure to Radon (BEIR VI), Phase II.

Glen R. Cass, California Institute of Technology, Pasadena, California.

Glen R. Cass is a professor of environmental engineering and mechanical engineering at the California Institute of Technology. He earned his Ph.D. in environmental engineering from the same institution. Research conducted by Professor Cass focuses on developing methods for identifying the least costly means of air pollution abatement in a complex regional setting. He is currently studying the formation and control of gaseous and fine particle pollutants, control strategies for visibility improvement, indoor air quality, economic optimization of pollution control strategies, and strategies for protection of works of art from damage due to air pollution. He is a member of the research advisory committee for the Health Effects Institute, and a consultant to both government and industry on air pollution and its control. He previously served on the EPA Clean Air Scientific Advisory Committee and on EPA's FACA subcommittee on ozone, fine particles, and regional haze. Dr. Cass served on the NRC Committee on Haze in National Parks and Wilderness Areas and the Committee on Preserving Historical Documents.

Judith C. Chow, Desert Research Institute, Reno, Nevada.

Dr. Judith C. Chow is a research professor at the Energy and Environmental Engineering Center, Desert Research Institute. She earned her Sc.D. in environmental science from Harvard University. She has been a major collaborator in more than 40 air quality studies and is currently co-principal investigator on several studies including the evaluation of aerosol measurement methods, sampling strategies, and data bases. She authored the Air & Waste Management Association's 1995 annual critical review on aerosol measurement methods and has over 100 peer-reviewed publications. She serves as chair of the Air & Waste Management Association's EM-2 Receptor Source Apportionment Technical Committee and as vice-chair of that organization's Measurement Division. She also serves as chair of the Metals 1 Subcommittee of the Intersociety Committee for Methods of Air Sampling and Analysis. Dr. Chow was Technical Program Chair for the Air and Waste Management Association's International Symposiurn on "$PM_{2.5}$: A Fine Particle Standard."

Bart E. Croes, California Air Resources Board, Sacramento, California.

Bart E. Croes is the chief of the Air Quality Data Branch at the California Air Resources Board. He received his B.S. in chemical engineering from the California Institute of Technology and his M.S. in chemical engineering from the University of California at Santa Barbara. He was the program manager for the 1997 Southern California Ozone Study and Aerosol Program, and former manager of atmospheric processes, particulate matter, and acid deposition research at the California Air Resources Board. He has served on several EPA review panels and various committees for NARSTO (North American Research Strategy for Tropospheric Ozone).

Robert E. Forster, The University of Pennsylvania School of Medicine, Philadelphia, Pennsylvania.

Robert Forster is Isaac Ott Professor Emeritus in the Department of Physiology at the University of Pennsylvania School of Medicine. He received his M.D. from the University of Pennsylvania, is a former chairman of the department of physiology at the University of Pennsylvania, past-president of the American Physiological Society, and was awarded a Von Humboldt Prize in 1993. Dr. Forster was elected to the National Academy of Sciences in 1973 and has served as chair of NAS Section 23 (Physiology and Pharmacology) and as a member of several NRC committees.

Daniel S. Greenbaum, Health Effects Institute, Cambridge, Massachusetts.

Daniel S. Greenbaum is the president and chief executive officer of the Health Effects Institute, an independent research institute funded jointly by government and industry to provide impartial and relevant research on the health effects of air pollution. He earned his Masters of City Planning from the Massachusetts Institute of Technology. At the Health Effects Institute, Mr. Greenbaum has overseen the development and implementation of a research plan that focuses the Institute's efforts on providing critical research and reanalysis on particulate matter, air toxics, and alternative fuels. Prior to joining the Health Effects Institute, he served as Commissioner of the Massachusetts Department of Environmental Protection.

Maureen Henderson, University of Washington, Seattle, Washington.

Maureen Henderson is professor emeritus of epidemiology and medicine at the University of Washington; and former Member of the Public Health Sciences Division at the Fred Hutchinson Cancer Research Center, where she was founder and head of the Cancer Prevention Research Program. Dr. Henderson received her M.B.B.S. (M.D.) and D.P.H. from the University of Durham, England, School of Medicine. She has been a member of the National Cancer Advisory Board and a member of the Advisory Council of the National Institute of Environmental Health Sciences. Dr. Henderson is a recipient of the Georgeana Seegar Jones Award for Lifetime Achievement in Women's Health Research and the John A. Snow Award (Epidemiology Section) from the American Public Health Association. She was elected to the NAS Institute of Medicine in 1974. She is a former member of the NRC Board on Radiation Effects Research, was chair of the Committee on the Epidemiologic Investigation of Air Pollutants, and has served on many other NRC committees.

Philip K. Hopke, Clarkson University, Potsdam, New York.

Philip Hopke is the Robert A. Plane Professor of Chemistry and Chair of the Department of Chemistry at Clarkson University. He earned his Ph.D. in chemistry from Princeton University. Prior to joining Clarkson University, he was a professor of environmental chemistry at the University of Illinois at Urbana-Champaign. His research interests include chemical characterization of airborne particles. He currently serves on the EPA Clean Air Science Advisory Committee (CASAC). He is a former director of the American Association of Aerosol Research and editor-in-chief of their Journal. He has served on six NRC committees, including the NRC Committee on Advances in Assessing Human Exposure to Airborne Pollutants. His most recent service has been on the NRC Committee on Health Risks of Exposure to Radon (BEIR VI), Phase 11 and the Committee on Risk Assessment of Exposure to Radon in Drinking Water.

Petros Koutrakis, Harvard School of Public Health, Boston, Massachusetts.

Petros Koutrakis is professor of environmental sciences and director of the Environmental Chemistry Laboratory at Harvard University. He received his Ph.D. in environmental chemistry from the University of Paris. His research interests include human exposure assessment, ambient and indoor air pollution, environmental analytical chemistry, and environmental management. He is technical editor-in-chief of the *Journal of the Air and Waste Management Association*, consultant to the EPA Science Advisory Board, and an advisor to the International Monitoring of Protected Visual Environments (IMPROVE), Panamerican Health Organization (PAHO), World Health Organization (WHO), and the United Nations Environmental Program.(UNEP). He has served on several EPA review panels and chaired the EPA Review Panel for Research Proposals on Ambient Particle Modeling.

Daniel Krewski, University of Ottawa, Ontario, Canada.

Dr. Krewski is professor of medicine and of epidemiology and community medicine at the University of Ottawa, and adjunct research professor of statistics at Carleton University. Previously, he served as director of Risk Management and as director of the Bureau of Chemical Hazards with Health Canada. He received his M.Sc. and Ph.D. in mathematics and statistics from Carleton University, and his M.H.A. from the University of Ottawa. Dr. Krewski is associate editor of *Risk Analysis* and the *Journal of Epidemiology and Biostatistics*. He is currently a member of the NRC Board on Environmental Studies and Toxicology and its Committee on Toxicology. He recently chaired the NRC's

Colloquium on Scientific Advances and the Future in Toxicologic Risk Assessment. He is also a member of the Committee on Research Priorities for Airborne Particulate Matter. Dr. Krewski has published more than 300 journal articles and book chapters in the areas of risk assessment, biostatistics, and epidemiology.

Paul James Lioy, University of Medicine and Dentistry-New Jersey, Piscataway, New Jersey.

Dr. Paul James Lioy is currently a professor of environmental and community medicine of UMDNJ-Robert Wood Johnson Medical School, and deputy director at the jointly sponsored Environmental and Occupational Medicine (EOHSI) of Rutgers, the State University of New Jersey and University of Medicine and Dentistry of New Jersey. Dr. Lioy received his Ph.D. in environmental sciences from Rutgers University. He has over 150 peer reviewed publications. His research interests include assessing human exposure to outdoor and indoor air pollutants, and techniques and field studies for characterizing atmospheric pollutants. He is a former chairman of the New Jersey Clean Air Council. He is a former member of the NRC's Board on Environmental Studies and Toxicology and five NRC committees. He served as chairman of the NRC Committee on Advances in Assessing Human Exposure to Airborne Pollutants. Currently, he serves on the Science Advisory Board of the U.S. EPA and is chair of the Subcommittee on Health and Ecological Effects Valuation. He is a member of the International Air Quality Board of the International Joint Commission of U.S./Canada.

Joe L. Mauderly, Lovelace Respiratory Research Institute, Albuquerque, New Mexico.

Dr. Joe L. Mauderly is a senior scientist and Director of External Affairs of the Lovelace Respiratory Research Institute, and president of its subsidiary, the Lovelace Biomedical and Environmental Research Institute. Dr. Mauderly received his D.V.M. from Kansas State University and specialized in respiratory physiology and comparative pulmonary responses to inhaled toxicants. He is past director of the Inhalation Toxicology Research Institute. He is a past chairman of the Environmental and Occupational Health Assembly of the American Thoracic Society and a past president and councilor of the Inhalation Specialty Section of the Society of Toxicology. He is a former chairman of the Electric Power Research Institute's Air Pollution Health Studies Advisory Committee and a former member of the Health Effects Institute's Research Committee. He is current chairman of EPA's Clean Air Scientific Advi sory Committee. He serves on the editorial boards of *Inhalation Toxicology* and *Experimental Lung Research,* and is former Associate Editor of *Fundamental and Applied Toxicology*. He also served as a member of the NRC Subcommittee on Pulmonary Toxicology.

Roger O. McClellan, Chemical Industry Institute of Toxicology, Research Triangle Park, North Carolina.

Roger McClellan is President Emeritus of the Chemical Industry Institute of Toxicology (CIIT) and adjunct professor of toxicology at Duke University, North Carolina State University and University of North Carolina-Chapel Hill. He served as President of CIIT from 1988 to 1999. Dr. McClellan earned his D.V.M. from Washington State University and is a diplomate of the American Board of Veterinary Toxicology and the American Board of Toxicology. He is a former president and director of the Inhalation Toxicology Research Institute, Lovelace Biomedical and Environmental Research Institute. He has served on numerous government advisory committees including the NIH toxicology study section, NIEHS advisory council, EPA's science advisory board and as chair of EPA's Clean Air Scientific Advisory Committee. He is a past president of the Society of Toxicology (SOT), the Inhalation Specialty Section of SOT, and American Association for Aerosol Research and a fellow of the Society for Risk Analysis, the Health Physics Society, and the American Association for Advancement of Science. He serves or has served on various editorial boards including *Journal of Fundamental and Applied Toxicology, Environmental Health Perspectives, Journal of Toxicology and Environmental Health,* and *Inhalation Toxicology* and serves as editor of *Critical Reviews in Toxicology*. He has received special awards from the Society of Toxicology, Health Physics Society, American Association for Aerosol Research, the International Society for Aerosols in Medicine, and the International Society of Regulatory Toxicology and Pharmacology. Dr. McClellan was elected to the Institute of Medicine in 1990. He is a former chair of the NRC's Committee on Toxicology and has served on several other NRC committees. He has a long-standing interest in the toxicology and assessment of human risks of airborne materials.

Günter Oberdörster, University of Rochester, Rochester, New York.

Günter Oberdörster is professor in the Department of Environmental Medicine and head of the Division of Respiratory Biology and Toxicology at the University of Rochester. He is internationally recognized for his research on the effects and underlying mechanisms of lung injury induced by inhaled non-fibrous and fibrous particles, including modeling and risk assessment. Dr. Oberdörster earned his D.V.M. and Ph.D. (med. vet.) from the University of

Giessen in Germany. He is a past-president of the Society of Toxicology's Inhalation Toxicology Specialty Section (ISS), a consultant to EPA's Clean Air Science Advisory Committee, a former member of the EPA Science Advisory Board's Subcommittee on Heavy Metals, a former member of the International Agency for Research on Cancer Committee, and a former member of the Board of Scientific Counselors of the National Toxicology Program. Dr. Oberdörster is a recipient of the Joseph von Fraunhofer Prize (Germany), the Society of Toxicology's ISS Career Achievement Award, and the Society of Toxicology's ISS 1997 Paper of the Year Award. He is on the editorial board of the *Journal of Aerosol Medicine and Inhalation Toxicology*. He is also currently a member of the NRC's Committee on Toxicology.

Rebecca Parkin, The George Washington University, Washington, D.C.

Dr. Rebecca Parkin is associate research professor at The George Washington University Medical Center. Dr. Parkin earned her M.P.H. in environmental health and her Ph.D. in epidemiology from Yale University. She is a former director of scientific, professional, and section affairs at the American Public Health Association as well as assistant commissioner for the Division of Occupational and Environmental Health of the New Jersey Department of Health. She is a member of the NRC Water Science and Technology Board, and has served on several NRC committees, including the Committee on Risk Assessment of Hazardous Air Pollutants. She is a liaison member of the National Advisory Committee on Childhood Lead Poisoning Prevention, and a peer reviewer for the New Jersey Cancer Research Commission. She has served on the Quality Management Subcommittee and the Modeling Studies Group of EPA's Science Advisory Board, and was a member of the Multisite Epidemiologic Studies Panel of ATSDR.

Joyce Penner, University of Michigan, Ann Arbor, Michigan.

Joyce Penner is a professor of atmospheric, oceanic, and space sciences at the University of Michigan-Ann Arbor. She earned her Ph.D. in applied mathematics from Harvard University. She is a former division leader of the Global Climate Research Division at the Lawrence Livermore National Laboratory. She is an Associate Editor for the *Journal of Geophysical Research* and the *Journal of Climate*. She was recently elected to the International Commission on Atmospheric Chemistry and Global Pollution. She is a member of the NRC Committee on Geophysical and Environmental Data and has served on the NRC Committee on Atmospheric Chemistry and the Panel on Aerosol Radiative Forcing and Climate Change.

Richard Schlesinger, New York University School of Medicine, Tuxedo, New York.

Dr. Richard Schlesinger is Professor of Environmental Medicine at New York University School of Medicine and is director of the Systemic Toxicology Program and the Laboratory for Pulmonary Biology and Toxicology. He received his Ph.D. in biology from New York University and has held a number of research and academic appointments at the NYU Medical School since 1969. He was a recipient of a Research Career Development Award from NIEHS and the Kenneth Morgareidge Award from the International Life Sciences Institute for contributions to the field of inhalation toxicology. He is a past-president of the Inhalation Specialty Section of the Society of Toxicology. He has served on EPA's Peer Review Panels for the Environmental Toxicology and Human Studies Divisions, and EPA's Expert Panel to Assess Needs for Ozone Research. Dr. Schlesinger is an Associate Editor of *Toxicology and Applied Pharmacology* and is on the editorial advisory board of *Inhalation Toxicology*. He has served on the NCRP Task Force for Dosimetry Modeling and on the NRC Subcommittee on Pulmonary Toxicology.

Frank Speizer, Harvard School of Public Health, Boston, Massachusetts.

Frank Speizer is professor of medicine at the Harvard Medical School, professor of environmental science at the Harvard School of Public Health, and a senior physician at Brigham and Women's Hospital and Beth Israel Hospital. Dr. Speizer received his M.D. from Stanford University Medical School. He has held a number of academic appointments at the Harvard University Medical School and School of Public Health since 1968. He has served on the Scientific Advisory Board of the American Lung Association/American Thoracic Society, and was a councillor to the Board of the International Society for Environmental Epidemiology. He is currently associate editor for *Environmental Research*. Dr. Speizer was a member of the NRC Committee on an Assessment of a Study of Possible Occupational Health Effects on Ionizing Radiation Among Nuclear Utility Workers and a member of the NRC Subcommittee on Pulmonary Toxicology.

Mark Utell, University of Rochester Medical Center, Rochester, New York.

Mark Utell is professor of medicine and environmental medicine at the University of Rochester School of Medicine. Dr. Utell earned his M.D. from Tufts University School of Medicine. He has been at the University of Rochester School of Medicine since 1975, holding a number of positions including director of the Pulmonary/Critical Care and Occupational Medicine Divisions'. Currently, he also serves as the Acting Chairman of Medicine. He has served on many national committees, including EPA's Science Advisory Board; EPA's Clean Air Science Advisory Committee, and NASA's Panel on Airborne Particulate Matter in Spacecraft. He is associate editor of *Environmental Research*. He is a recipient of the NIEHS Academic Award in Environmental and Occupational Medicine. Dr. Utell currently serves on the NRC Committee on the Evaluation of the Department of Defense Comprehensive Clinical Evaluation Protocol and has served on several other NRC committees.

Ronald H. White, American Lung Association, Washington, DC.

Ronald H. White is Director of National Programs at the American Lung Association. He earned his Master of Science in environmental studies from Antioch University in 1978. Prior to joining the American Lung Association, he was a senior transportation/air quality planner and then a public participation coordinator with the Tri-State Regional Planning Commission in New York. He has served as a member of the Integrated Human Exposure Committee of the EPA Science Advisory Board, as well as on the EPA Blue Ribbon Panel to review the use of oxygenates in gasoline. Mr. White currently serves on the science advisory committees for several air pollution health effects research projects.

Warren H. White, Washington University, St. Louis, Missouri.

Warren H. White is a senior research associate at Washington University, St. Louis, Missouri. He received his Ph.D. in mathematics from the University of Wisconsin. Dr. White's research focuses on airborne particles and visibility impairment. He served on the review panel for the PM Criteria Document and is currently a member of the EPA Clean Air Science Advisory Committee (CASAC) and its PM monitoring subcommittee. He is on the NRC's Committee to Assess the North American Research Strategy for Tropospheric Ozone (NARSTO) Program and is a source of coordination with that committee, whose work is highly relevant to the present committee. He previously served as a member of the NRC Committee on Haze in National Parks and Wilderness Areas.

Ronald Wyzga, Electric Power Research Institute, Palo Alto, California.

Ronald Wyzga is Technical Executive of the Air Quality, Health, and Risk Area of EPRI (Electric Power Research Institute). He received his A.B. in mathematics from Harvard College, his M.S. in statistics from Florida State University, and his Sc.D. in biostatistics from Harvard School of Public Health. He has held various research and managerial positions within EPRI since 1975, including senior manager of Air Quality and Risk. He has been involved in air quality research on particulate matter, ozone, air toxics, and visibility issues. He is a fellow of the American Statistical Association. He previously served with the Organization for Economic Cooperation and Development in Paris, where he coauthored a book on evaluation of environmental damage. He has served on several committees of the NRC and EPA's Science Advisory Board.

Terry F. Yosie, Chemical Manufacturer's Association, Arlington, Virginia.

Terry Yosie is vice president of Strategic Communications at Chemical Manufacturers Association. He earned his doctorate from the College of Humanities and Social Sciences at Carnegie Mellon University. He has approximately twenty years of professional experience in managing and analyzing the use of scientific information in the setting of environmental standards. From 1978 to 1981, he was the first Executive Director of the Clean Air Scientific Advisory Committee (CASAC) which is responsible for reviewing the scientific basis of National Ambient Air Quality Standards. He served as Director of EPA's Science Advisory Board (1981–1988) and as Vice President for Health and Environment at the American Petroleum Institute (1988–1992). From 1992 to 1999, Dr. Yosie was executive vice president of Ruder Finn, Inc. where he was responsible for the firm's environmental management practice. He was a member of the NRC Committee to Review the Structure and Performance of the Health Effects Institute and currently serves on the NRC's Board on Environmental Studies and Toxicology. He is also a consultant to EPA's Science Advisory Board.

Appendix B

THE COMMITTEE'S STATEMENT OF TASK

The committee will assess research priorities, develop a conceptual research plan, and monitor research progress toward improved understanding of the relationships between airborne particulate matter (PM), its various sources, and its effects on public health. The study will focus on PM-related research being conducted, funded, or planned by the U.S. Environmental Protection Agency (EPA) in the context of PM-related research being conducted, funded, or planned by other agencies and organizations in the United States and abroad.

Four reports will be prepared. The first report, required by Congress within four months of project initiation, will identify the most important short-term and longer-term research priorities relevant to evaluating, setting, and implementing primary National Ambient Air Quality Standards (NAAQS) for particulate matter (PM). The second report will expand upon the assessment of research priorities and present conceptual plans for the monitoring and evaluation of research. Subsequent reports at the end of the third and fifth years will evaluate research progress and update the research priorities and plans as warranted.