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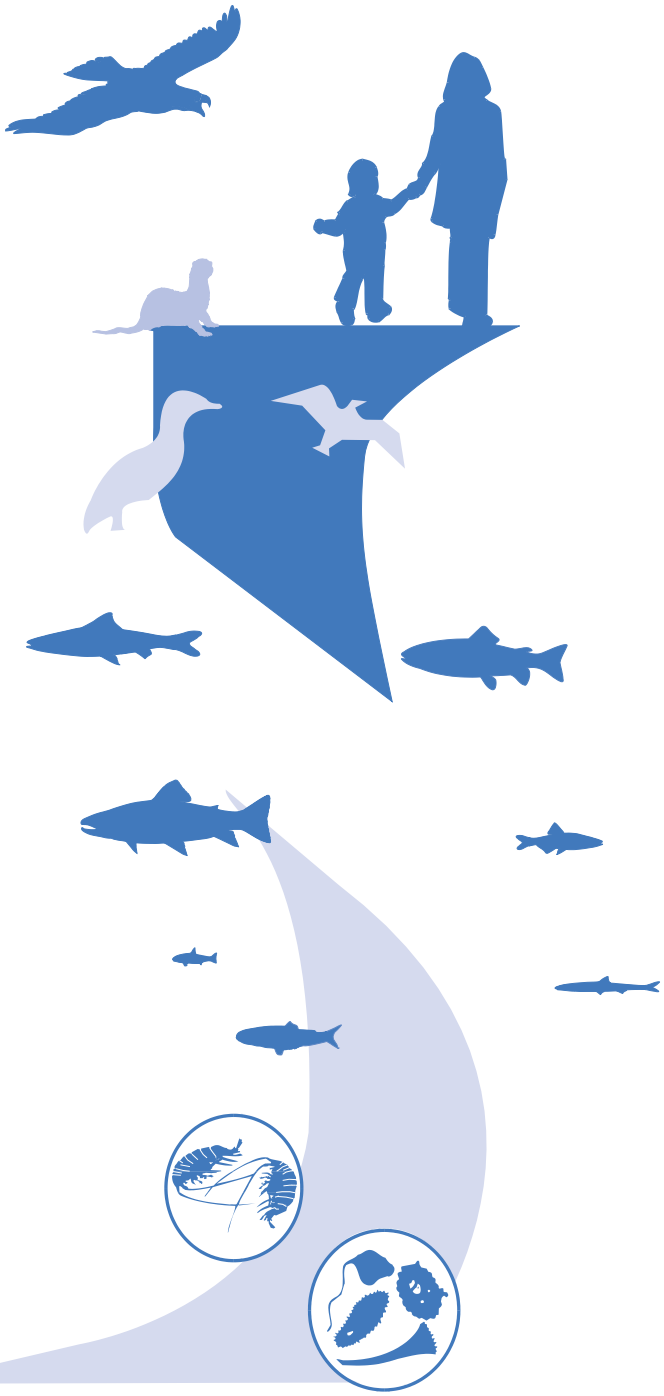
Mercury Research Strategy



On the Cover: This graphic, originally used on the cover of the *Mercury Study Report to Congress (Report to Congress)*, depicts the pathway through which mercury contamination proceeds to humans and wildlife. It emphasizes the transport, transformation, and fate of mercury through the aquatic food web. Such a pathway includes the biological conversion of atmospherically-deposited mercury to an organic form (i.e., methylmercury); the uptake and bioaccumulation of methylmercury in fish, birds, and mammals; and the subsequent health effects on susceptible populations who consume large quantities of methylmercury-contaminated fish such as women of child bearing age (i.e. maternal/fetal pair), and young children. Prepared by the U. S. Environmental Protection Agency (EPA), the *Report to Congress* supports a plausible link between anthropogenic releases of mercury from industrial and combustion sources in the U.S. and the concentration of methylmercury in fish. The *Report to Congress*, along with several other EPA reports, serve as drivers for the preparation of the *Mercury Research Strategy*.

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September 2000

Mercury Research Strategy

Office of Research and Development
National Risk Management Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, OH 45268

NOTICE

This document has been reviewed in accordance with U. S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's Office of Research and Development (ORD) is providing data and technical support for solving environmental problems today, and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The 1996 *Strategic Plan for the Office of Research and Development*, and subsequent updates, sets forth ORD's vision, mission, and long-term research goals. The Strategic Plan thus serves as the foundation for all of the research strategies and plans that ORD has developed, or is in the process of developing. As part of its strategic planning process, ORD uses the risk paradigm to identify EPA's top research priorities for the future. This focus on the risk paradigm helps in establishing the individual, high priority topics for which research strategies are prepared. One of the high priority research topics identified as part of the strategic planning process deals with the assessment and management of mercury and methylmercury risks.

The *Mercury Research Strategy* describes the strategic approach for ORD's mercury research program. Using as a technical foundation the EPA 1997 *Mercury Study Report to Congress*, the *Mercury Research Strategy* presents the key scientific questions to be addressed over the next five years. It also describes the research needed to answer those questions. The *Mercury Research Strategy* not only provides strategic directions, but serves as an important budget tool. It is central to the preparation of a multi-year implementation plan for mercury and methylmercury research. This multi-year plan enables EPA to track the progress being made in the mercury research program, as required by the 1993 Government Performance and Results Act.

Much of the research described in the *Mercury Research Strategy* will be conducted by ORD's in-house laboratories and assessment center. ORD's Science to Achieve Results (STAR) Grants Program is also sponsoring research to investigate several of the identified research needs. In some cases, ORD scientists and engineers are already working in close cooperation with federal and state organizations in conducting research on mercury and methylmercury. Many organizations may see opportunities to collaborate in one or more of the research areas described in the *Mercury Research Strategy*. ORD welcomes such collaborations in addressing the needs identified and invites those interested to suggest joint activities.

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PEER REVIEW

Peer review is an important component of research strategy development. The peer review history for the *Mercury Research Strategy* is as follows:

Initial Internal Agency Review:	September 1998
ORD Science Council:	Final clearance November 1998
Lead Reviewer:	Lee Mulkey, Ecology Associate National Risk Management Research Laboratory
Submitted for Comments to the Draft *Mercury Research Strategy* Peer Review Panel:	October 1999
External Peer Review:	December 8 – 9, 1999; Washington, DC

Reviewers:

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Final Acceptance by ORD:	September 2000
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ACKNOWLEDGMENTS

The *Mercury Research Strategy* was prepared by Office of Research and Development scientists and engineers and technical staff from EPA's Program Offices and Regions. Co-leaders for ORD were Jonathan Herrmann of the National Risk Management Research Laboratory and Kathryn Mahaffey, formerly of the National Center for Environmental Assessment, now with the Office of Prevention, Pesticides, and Toxic Substances. Major contributors included:

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ACRONYMS

ACAP	Arctic Council Action Plan
AEPS	Arctic Environmental Protection Strategy
AMAP	Arctic Monitoring and Assessment Program
APGs	Annual Performance Goals
APMs	Annual Performance Measures
ARL	Atmospheric Research Laboratory
ATSDR	Agency for Toxic Substances and Disease Registry
BAT	Best Available Technology
BBDR	Biologically Based Dose-Response
BIFs	Boilers and Industrial Furnaces
BMDL	Benchmark Dose Lower Bound
BNS	Binational Toxics Strategy
CAA	Clean Air Act
CEC	Commission for Environmental Cooperation
CEMs	Continuous Emission Monitors
CENR	Committee on the Environment and Natural Resources
CETEM	Center for Mineral Technology
DOD	Department of Defense
DOE	Department of Energy
DOS	Department of State
ELA	Experimental Lakes Area
EMAP	Environmental Monitoring and Assessment Program
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EWG	Environmental Working Group
FDA	Food and Drug Administration
GLI	Great Lakes Water Quality Initiative
GLNPO	Great Lakes National Program Office
GPRA	Government Performance and Results Act
HAPs	Hazardous Air Pollutants
HCl	Hydrochloric Acid
Hg	Mercury
Hg^0	Elemental Mercury Vapor
Hg^{+2}	Gas-Phase Ionic Mercury
Hg_p	Particulate-Bound Mercury
$HgCl_2$	Mercuric Chloride
HWIs	Hazardous Waste Incinerators
ICR	Information Collection Request
LCA	Life Cycle Assessment
LDRs	Land Disposal Restrictions
LOAEL	Lowest Observed Adverse Effect Level
LRTAP	Long Range Transboundary Air Pollution
MACT	Maximum Achievable Control Technology
MCCAPs	Mercury-Cell Chlor Alkali Plants
MCM	Mercury Cycling Model
MRL	Minimal Risk Level
MRS	Mercury Research Strategy
MTF	Mercury Task Force
MWCs	Municipal Waste Combustors

ACRONYMS (cont.)

MWIs	Medical Waste Incinerators
NAAEC	North American Agreement on Environmental Cooperation
NARAP	North American Regional Action Plan
NAS	National Academy of Sciences
NCEA	National Center for Environmental Assessment
NCER	National Center for Environmental Research
NCHS	National Center for Health Statistics
NEG/ECP	New England Governors/Eastern Canadian Premiers
NEP	National Estuary Program
NERRS	National Estuarine Research Reserves System
NESCAUM	Northeast States for Coordinated Air Use Management
NETL	National Energy Technology Laboratory
NHANES	National Health and Nutrition Examination Survey
NHEERL	National Health and Environmental Effects Research Laboratory
NIH	National Institutes of Health
NIEHS	National Institute for Environmental Health Sciences
NOAA	National Oceanic and Atmospheric Administration
NOAEL	No Observed Adverse Effect Level
NO_x	Oxides of Nitrogen
NRC	National Research Council
NRDC	National Resources Defense Council
NRMRL	National Risk Management Research Laboratory
NTI	National Toxics Inventory
NWF	National Wildlife Federation
OAQPS	Office of Air Quality Planning and Standards
OAR	Office of Air and Radiation
OERR	Office of Emergency and Remedial Response
OIA	Office of International Activities
OPPTS	Office of Prevention, Pesticides, and Toxic Substances
ORD	Office of Research and Development
ORNL	Oak Ridge National Laboratory
OSTP	Office of Science and Technology Policy
OSW	Office of Solid Waste
OSWER	Office of Solid Waste and Emergency Response
OW	Office of Water
PAC	Powdered Activated Carbon
PAME	Protection of the Arctic Marine Environment
PBPK	Physiologically-Based Pharmacokinetics
PBTs	Persistent, Bioaccumulative Toxics
PCBs	Polychlorinated Biphenyls
PM	Particulate Matter
ppb	Parts Per Billion
ppm	Parts Per Million
RCRA	Resource Conservation and Recovery Act
RELMAP	Regional Lagrangian Model of Air Pollution
RFA	Request for Application
RfD	Reference Dose
RGM	Reactive Gaseous Mercury
SMOC	Sound Management of Chemicals

ACRONYMS (cont.)

SO_2	Sulfur Dioxide
SO_3	Sulfur Trioxide
STAR	Science to Achieve Results
TCDD	2,3,7,8-tetrachlorodibenzo-p-dioxin
TMDLs	Total Maximum Daily Loads
TRI	Toxics Release Inventory
UNECE	United Nations Economic Commission for Europe
USGS	United States Geological Survey
WC	Wildlife Criterion
WHO	World Health Organization

EXECUTIVE SUMMARY

INTRODUCTION

The *Mercury Research Strategy (MRS)* guides the Office of Research and Development (ORD) mercury research program. Mercury has been identified as an important human health and environmental problem in a number of U.S. Environmental Protection Agency (EPA) documents such as the *Study of Hazardous Air Pollutant Emissions from Electric Utility Steam Generating Units – Final Report to Congress* (EPA, 1998b) and the *Deposition of Air Pollutants to the Great Waters: Third Report to Congress* (EPA, 2000a). The *MRS*, called for in EPA's draft *Mercury Action Plan* (Federal Register, 1998), covers FY2001– 2005. It summarizes the human health and ecological risks posed by mercury and methylmercury, and indicates that mercury needs to be considered on local, regional, and global scales. The *MRS* identifies the key scientific questions of greatest importance to the Agency. It then describes a research program to answer those questions. The goal of the *MRS* is to reduce the scientific uncertainties that limit EPA's ability to assess and manage mercury and methylmercury risks. ORD will use the *Mercury Research Strategy* to develop a multi-year implementation plan in FY 2001 for its mercury research program.

In conducting the mercury research program, in-house research efforts by ORD's laboratories and assessment center will be coupled with those of ORD's Science to Achieve Results (STAR) Grants Program. The STAR Grants Program sponsors extramural research with academic institutions and other not-for-profit entities. Also, some of the research described in the *MRS* will be undertaken in cooperation with organizations such as the Department of Energy and the U.S. Geological Survey. The *MRS* provides information on research needs and priorities that can be used by various stakeholders outside of the Agency, including researchers in other federal agencies, states, private industry, not-for-profit organizations, and academia. It may well assist them in planning their own mercury research activities and programs. Finally, the *Mercury Research Strategy* suggests that other scientific data and information not generally considered "research" are needed, such as inventories of sources and routine multimedia monitoring.

EPA Report: *Mercury Study Report to Congress*

The *Mercury Study Report to Congress (Report to Congress)* (EPA, 1997a) described the magnitude of mercury emissions in the United States, identified mercury emission sources, assessed the health and environmental implications of those emissions, and evaluated the availability and cost of technologies for emission control. It is the most comprehensive human health and environmental investigation of mercury and methylmercury available. The *Report to Congress* serves as the foundation for EPA's understanding of the risk assessment and risk management issues associated with mercury and methylmercury. It contributes significantly to the strategic directions and the key scientific questions posed in the *Mercury Research Strategy*.

In the *Report to Congress*, EPA concluded that a plausible link exists between human activities that release mercury from industrial and combustion sources in the United States and methylmercury concentrations in humans and wildlife. In preparing the report, EPA conducted a quantitative human health risk assessment of methylmercury. The assessment estimated that between one and three percent of women of childbearing age (*i.e.,* between the ages of 15 and 44 years) in the United States eat sufficient amounts of fish for their fetuses to be at risk from methylmercury exposure. The *Mercury Study Report to Congress* also concluded that mercury poses risks to various wildlife, including some birds and fur bearing mammals such as loons, mink, and otters. The *Report to Congress* comprehensively identified research needs to improve both mercury risk assessment and risk management.

NAS Report: *Toxicological Effects of Methylmercury*

The National Academy of Sciences (NAS) report on the *Toxicological Effects of Methylmercury* (NRC, 2000) confirmed EPA's Reference Dose (RfD) of 0.1 micrograms per kilogram of body weight per day. It viewed this RfD as a scientifically justifiable level for protecting human health from the adverse effects

of methylmercury. The NAS report estimated that more than 60,000 U.S. children are born each year with a risk of damaged nervous systems from methylmercury exposures in the womb. It also noted reduced performance on neuropsychological tests in recent epidemiological studies, suggesting that prenatal methylmercury exposure is likely to be associated with poorer school performance. The NAS report identified research needs related to: better characterization of methylmercury heath effects, enhanced estimation of methylmercury dose-response relationships, and improved characterization of risk from current methylmercury exposures. Finally, the NAS report recommended that every effort be made to establish a common scientific basis for exposure guidance among federal agencies, recognizing that each is responsible under differing legal and regulatory authorities.

MERCURY IN THE ENVIRONMENT

As a liquid at room temperature, mercury is a unique metal that has proven itself useful for centuries in both industrial and consumer applications. Mercury is released in elemental and oxidized forms from a variety of human (i.e., anthropogenic) activities and natural sources. The *Mercury Study Report to Congress* (EPA, 1997a) found that the exposure pathway of greatest concern is that of fish consumption. This pathway is the one emphasized in the *Mercury Research Strategy* and involves the following: (1) emission of mercury to the air; (2) mercury air transport, transformation, and deposition on land and water; (3) transformation of mercury to methylmercury in water bodies; (4) methylmercury uptake and bioaccumulation in fish; and (5) consumption of contaminated fish by mammals, including humans. Mercury and methylmercury exposures can result in permanent damage to the brain and kidneys in both humans and wildlife.

The intentional use of mercury in products (*e.g.,* batteries, paints) in the United States has decreased significantly in the past twenty years (Sznopoek and Goonan, 2000). Since the 19th Century, however, the total amount of mercury in the environment has grown by a factor of two to five above pre-industrial levels (Mason, et. al.,1994). This situation raises concerns about increasing amounts of mercury in the global pool and the implications of mercury emissions and their impacts on both people and ecosystems worldwide. In the United States, the most significant releases of mercury to the environment are emissions to the air. These air emissions come from combustion sources, such as power plants or incinerators (mercury from human activities). Mercury is also released from geologically bound sources through natural processes (*e.g.*, volcanos, fires) and through mass transfer to the atmosphere by biologic and geologic processes from mercury that has been previously deposited (*i.e.*, re-emitted sources). In addition to air emissions, mercury is also released in other ways, including waterborne discharges and direct disposal to the land. The release of mercury to water and land are believed to be small compared to air emissions, but these releases can have significant local effects.

Depending on the chemical form in which it is released, the stack height of the source, air movement patterns, and other factors, mercury can deposit at local, regional and global scales.

- Locally, the 30-mile radius from some sources can have a relatively high percentage of mercury depositing on land and water.

- Regionally, different areas of the country experience different amounts of mercury deposition; the combined emissions of several mercury sources can travel hundreds of miles and deposit in other regions of the United States.

- Globally, mercury from other countries deposits in the United States, and U.S. emissions can travel around the world and then deposit back on U.S. soil and water.

Modeling by EPA concluded that the highest regional deposition rates from U.S. anthropogenic mercury sources occur in the southern Great Lakes and Ohio Valley, the Northeast, and scattered areas in the Southeastern United States (EPA, 1997a).

The particular form of mercury emitted is important in determining whether it is deposited near its emission source or travels great distances, perhaps circling the globe several times before eventually depositing. Mercury emissions from human activities are comprised of various inorganic forms, including elemental mercury vapor, gas-phase ionic mercury, and particulate-bound mercury. Once deposited in the environment, these inorganic forms can be converted by naturally occurring processes into the highly toxic organic form — methylmercury. The greatest concern regarding methylmercury is the neurotoxic health effects associated with in utero exposures. Children exposed after birth are potentially more sensitive to the toxic effects of methylmercury than adults because their nervous systems are still developing. Mercury also poses risks to wildlife, including some birds and mammals, such as loons, mink, and otters.

Mercury Research Strategy Goal

To provide information and data that reduce scientific uncertainties limiting the Agency's ability to assess and manage mercury and methylmercury risks.

MERCURY RESEARCH STRATEGY SCOPE

ORD's mercury research program provides information, methods, models and data to address the key scientific questions of greatest concern to EPA. The *Mercury Research Strategy* goal seeks to reduce scientific uncertainties related to mercury and methylmercury. The *MRS* presents the strategic directions for the mercury research program over the next five years. It will assist ORD in the development of a multi-year implementation plan and will help in making decisions about future mercury research priorities. The results of the research program will inform the Agency's Program Offices and Regions on their actions to assess and manage mercury and methylmercury risks. The *Mercury Research Strategy* is oriented to domestic mercury and methylmercury issues, although most of the research results will also be useful internationally. In preparing the *Mercury Research Strategy*, six key scientific questions, associated research areas, and related research needs were identified. While it is a five-year research strategy, the *MRS* will undergo updates and adjustments based on ORD's annual research planning process.

While the NAS report confirmed EPA's reference dose for methylmercury, additional data and information are needed to answer a number of key scientific questions on risk assessment and risk management of mercury and methylmercury. ORD's *Mercury Research Strategy* is part of the Agency's *Sound Science, Improved Understanding of Environmental Risk, and Greater Innovation to Address Environmental Problems Goal (Goal 8)*. Implementation of Goal 8 is the responsibility of EPA's Office of Research and Development under the Government Performance and Results Act (GPRA) (EPA, 2000b). Although assigned to Goal 8, ORD's mercury research program supports a number of other GPRA goals including those related to clean air, clean water, and safe waste management.

Mercury Research Strategy Research Areas

Transport, Transformation, and Fate
Risk Management for Combustion Sources
Risk Management for Non-Combustion Sources
Human Health Effects and Exposure
Ecological Effects and Exposure
Risk Communication

Setting Research Priorities

The *MRS* was developed by a group of EPA scientists and engineers representing ORD and the Agency's Program Offices and Regions. To draft the strategy, the group was divided into eight writing teams focusing on a number of different aspects of mercury and methylmercury risk assessment and risk management. The teams consulted a number of documents and individuals in preparing the *MRS*; the most influential was the *Mercury Study Report to Congress* which identified research needs across a number of areas. The writing teams developed six scientific questions formed around the research needs identified in the *Report to Congress* and from other sources, including the Agency's Mercury Task Force (MTF).

The writing teams established the research needs for each of the six key scientific questions. The MTF assisted in this effort by identifying the regulatory and voluntary drivers for mercury and methylmercury facing the Agency over the next five years. The writing teams integrated relevant international research issues into each research area. Research needs under each key scientific question were prioritized using three criteria. These criteria were: (1) provides timely scientific information and data needed to inform current and future Agency decisions on mercury, (2) fills data and information gaps on mercury not addressed by other organizations, and (3) supports the goals and objectives of ORD's Strategic Plan and research on risk assessment and risk management. Finally, an expert panel of ten external peer reviewers offered their individual and collective opinions of the draft *Mercury Research Strategy* and its priorities in December of 1999. Many of the recommendations made by the peer panel have been incorporated into this final version of the *MRS*.

Every attempt was made by the writing teams to strike a balance in terms of priorities across the six key scientific questions. The priorities described in the *MRS* are only a snapshot in time and may well require adjustment in the coming five years. Priorities can change depending on a number of factors including: progress in answering the key scientific questions, changes in regulatory deadlines, and research contributions by other organizations. These factors require that priorities and resource allocations be revisited on a year-to-year basis and that flexibility be a guiding principle in the annual budgeting process for the mercury research program.

In the near term, ORD plans to focus on combustion risk management. In the longer term, ORD will emphasize research that enhances the fundamental understanding of: non-combustion risk management, ecological effects and exposure, human health effects and exposure, and risk communication. Mercury fate and transport research will be a focus throughout the five-year time frame of the *MRS*. The *Mercury Research Strategy* is aligned with current EPA Program Office and Regional priorities and emphasizes mercury sources resulting from human activities in the United States. It does, however, recognize the global nature of the mercury problem and the need for addressing impacts in the United States from emissions generated by other nations. The *Mercury Research Strategy* is designed to be flexible and can accommodate redirections as a result of changing Agency priorities and perspectives.

TRANSPORT, TRANSFORMATION AND FATE RESEARCH AREA

Key Scientific Question

How much methylmercury in fish consumed by the U.S. population is contributed by U.S. emissions relative to other sources of mercury (such as natural sources, emissions from sources in other countries, and re-emissions from the global pool); how much and over what time period, will levels of methylmercury in fish in the U.S. decrease due to reductions in environmental releases from U.S. sources?

Prioritized Research Needs

- Improved understanding of the transport, transformation, and fate of mercury in the atmosphere
- Enhanced monitoring of atmospheric mercury deposition for model application
- Improved understanding of the transport, transformation, and fate of mercury in the aquatic and terrestrial media
- Enhanced monitoring of mercury and methylmercury in the aquatic and terrestrial media for improved risk management

Research on transport, transformation, and fate is highly supported throughout the life of the *Mercury Research Strategy*. Research needs in this area will take some time to fully address because the transport, transformation, and fate of mercury is so complex once it enters the environment. This research will allow for an improved understanding of mercury in air and water, and on land. As fundamental understanding is improved, this research will inform the development of more cost-effective risk management approaches for mercury and methylmercury.

RISK MANAGEMENT FOR COMBUSTION SOURCES RESEARCH AREA

Key Scientific Question

How much can mercury emissions from coal-fired utility boilers and other combustion systems be reduced with innovative mercury and multi-pollutant control technologies; what is the relative performance and cost of these new approaches compared to currently available technologies?

Prioritized Research Needs

- Improved understanding of managing mercury species in combustion processes
- Improved understanding of performance and cost of mercury emissions controls
- Increased testing and evaluation of mercury continuous emission monitors
- Improved characterization of, and management approaches for, mercury controls residuals

Research to manage risks from combustion sources addresses the most immediate mercury priority for the Agency and is highly supported during the first years of the *Mercury Research Strategy*. Combustion risk management research, including research on mercury in controls residuals, will provide the Agency with the latest information on control technology performance and cost. This research will result in data and information that informs the preparation of a regulatory proposal for controlling mercury emissions from coal-fired utilities.

RISK MANAGEMENT FOR NON-COMBUSTION SOURCES RESEARCH

Key Scientific Question

What is the magnitude of contributions of mercury releases from non-combustion sources; how can the most significant releases be minimized?

Prioritized Research Needs

- Characterization of the mercury life cycle in human activities
- Improved understanding of mercury releases from sources and sinks
- Approaches for minimizing mercury releases from non-combustion sources

Research to manage risks from non-combustion sources is modestly supported in the early years of the *Mercury Research Strategy*. Work in this area then increases as the need for risk management research on coal-fired utilities declines and other sources of mercury releases come to the fore. Initial activities will focus on characterizing sources and identifying alternatives to mercury-containing waste incineration. Work in later years will address pollution prevention, source control, stockpile retirement, and remediation of contaminated media. With thorough source characterization, this research will focus on mercury sources posing the greatest risks to both humans and wildlife. This research will provide information to support future assessments, rulemaking, and voluntary actions across the Agency.

ECOLOGICAL EFFECTS AND EXPOSURE RESEARCH

Key Scientific Question

What are the risks associated with methylmercury exposure to wildlife species and other significant ecological receptors?

Prioritized Research Needs

- Improved understanding of methylmercury toxicity effects on avian and mammalian wildlife
- Refined ecological assessments for avian and mammalian wildlife risks
- Improved understanding of ecological impacts of methylmercury on avian and mammalian wildlife
- Improved understanding of ecological impacts of methylmercury on non-avian and non-mammalian species
- Identification of interactions among methylmercury with other chemical and non-chemical stressors on all ecological receptors

The effects of methylmercury on ecological systems have been demonstrated, but there is a need to learn more about these effects, particularly with respect to fish-eating wildlife. Support for this research area gradually increases over the life of the *Mercury Research Strategy*. This research will assist the Agency in understanding the effects and exposures of mercury and methylmercury on birds, fur-bearing mammals, and other forms of animal life. This research will also assist in the development of improved ecological assessments.

HUMAN HEALTH EFFECTS AND EXPOSURE RESEARCH

Key Scientific Question

What critical changes in human health are associated with exposure to environmental sources of methylmercury in the most susceptible human population; how much methylmercury are humans exposed to, particularly women of child-bearing age and children among highly-exposed population groups; what is the magnitude of uncertainty and variability of mercury and methylmercury toxicokinetics in children?

Prioritized Research Needs

- Improved understanding of mechanisms of developmental neurotoxicity from methylmercury
- Improved understanding of persistent and delayed neurotoxicity resulting from developmental exposures to methylmercury
- Identification of impacts from aggregate exposures and synergistic effects of methylmercury and other pollutants
- Improved understanding of the modulation of immune system response from methylmercury exposure
- Improved understanding of the effects on cardiovascular function as a result of methylmercury exposure
- Biological monitoring for model development and improvement
- Development of toxicokinetic data on methylmercury tissue distribution

The National Academy of Sciences (NAS) report on the health effects of methylmercury supported EPA's reference dose (RfD) of 0.1 micrograms per kilogram body weight per day as a scientifically-justified level to protect human health. There remain, however, questions that need to be answered. Research in this area is supported at a relatively modest, but consistent, level throughout the life of the *Mercury Research Strategy*. There is a continuing need for ORD to provide scientific and technical assistance to the Agency in developing regulations and criteria based on the NAS-supported RfD.

RISK COMMUNICATION RESEARCH

Key Scientific Question

What are the most effective means for informing susceptible populations of the health risks posed by mercury and methylmercury contamination of fish and seafood?

Prioritized Research Needs

- Synchronization of fish consumption advisory messages for methylmercury
- Improved understanding of exposure patterns in targeting of risk messages
- Understanding the use of risk information in making decisions about methylmercury exposures

Research on improved communication to populations at risk from eating fish contaminated with methylmercury is supported at a relatively modest, but consistent, level over the life of the *Mercury Research Strategy*. Research in this area will help the Agency in developing improved risk communication approaches targeted at populations that consume large quantities of fish. One of the most challenging populations will be those individuals at greater risk due to possible nervous system damage such as the maternal-fetal pair, nursing mother-infant pair, and young children. This research area as one that is particularly amenable to collaborations with other organizations.

MERCURY RESEARCH STRATEGY IMPLEMENTATION

A number of groups, both internal and external to EPA, have a stake in the *Mercury Research Strategy* and its implementation over the next five years. These groups are particularly interested in research program sequencing and timing in order to determine whether they are consistent with their needs, interests, and with Agency target dates for regulatory and voluntary actions. The *MRS* is designed to provide broad strategic directions for ORD's mercury research program, not schedules and time lines. More specific information will be forthcoming in ORD's multi-year implementation plan to be developed in FY 2001.

The *Mercury Research Strategy* encourages engagement and partnering with various stakeholders. ORD believes that joint ventures enhance the Agency's own mercury research program, as well as other mercury research efforts either planned or underway in the United States. It wants to strengthen research collaborations with the regulated community and other interested entities and gain their participation in mutually beneficial mercury research. ORD is seeking linkages to federal agencies, States, communities, tribes, and other public and private organizations in order to gather insights from decision makers at various levels. Of particular interest are their mercury research needs and the actions they expect to take in both assessing and managing mercury risks. ORD welcomes input from any organization concerning the *Mercury Research Strategy* and the mercury research program described herein.

1.0 INTRODUCTION

1.1 BACKGROUND

Mercury is a naturally occurring element that is neither created nor destroyed. It enters the environment as a result of natural (*e.g.,* volcanos, fires, surface emissions) and human (*e.g.,* combustion, commercial products) activities (i.e. anthropogenic sources). Depending on the situation, once deposited on land or water mercury can re-enter the atmosphere. Mercury is found in the environment as an inorganic (*e.g.,* elemental mercury vapor [Hg^0], gas-phase ionic mercury [Hg^{+2}], particulate-bound mercury [Hg_p]), and in organic forms (*e.g.,* methylmercury). It is emitted from human activities in the inorganic form[1]. Over the years, some mercury compounds have been specifically developed as pesticides, fungicides, and germicides to be used on grains, in paints, and with vaccines.

> The amount of mercury released into the biosphere has increased since the beginning of the industrial age. Mercury in the atmosphere can be transported thousands of miles from sources of emission and can circulate in the atmosphere for up to a year. Most of the mercury in water, soil, sediments, or plants and animals is in the form of inorganic mercury salts and organic mercury (e.g., methylmercury). The inorganic form of mercury, when either bound to airborne particles or in a gaseous form, is readily removed from the atmosphere by precipitation and is also dry deposited. As it cycles among the atmosphere, land, and water, mercury undergoes a series of complex chemical and physical transformations, many of which are not completely understood.
>
> Excerpt from the Executive Summary of the *Mercury Study Report to Congress*, Volume 1, December 1997 (EPA, 1997a).

Mercury and its compounds are persistent, bioaccumulative and toxic, and they pose human and ecosystem risks. The intentional use of mercury in products (*e.g.,* batteries, paints) has decreased significantly in the past twenty years (Sznopoek and Goonan, 2000). Since the 19th Century, however, the total amount of mercury in the environment has increased by a factor of two to five above pre-industrial levels (Mason, et. al, 1994). As the quantity of available mercury in the environment has increased, so too have the risks of neurological and reproductive problems for humans and wildlife. This makes mercury a pollutant of increasing environmental concern in the United States, and throughout the world.

The 1997 *Mercury Study Report to Congress* improved EPA's understanding of mercury and its impacts. The Agency prepared the *Mercury Study Report to Congress* in response to Title III, section 112 (n)(1)(B) of the Clean Air Act Amendments (CAA) of 1990 (U.S. Congress, 1990). In that legislation, Congress directed EPA's Administrator to conduct ". . . a study of mercury emissions from electric utility steam generating units, municipal waste combustion units, and other sources, including area sources." As part of the study, the Agency was asked to consider mercury emissions: (1) rate and mass, (2) health and environmental effects, and (3) control technologies, including the costs of such technologies. In carrying out the study, EPA modeled the emissions of major anthropogenic sources in the United States and concluded that there was ". . . a plausible link between anthropogenic releases[2] of mercury from industrial and combustion sources in the United States and methylmercury in fish"(EPA, 1997a). The *Mercury Study Report to Congress* also concluded that the fish ingestion exposure pathway was the route of greatest interest for stack-emitted mercury. As part of the report, EPA conducted a quantitative human health risk assessment of methylmercury based on fish consumption surveys. This risk assessment estimated that between one and three percent of women of childbearing age (i.e. between the ages of 15 and 44 years) eat sufficient amounts of fish for their fetuses to be at risk from methylmercury exposure.

In addition to the *Mercury Study Report to Congress*, a number of other EPA documents have demonstrated the need for the *Mercury Research Strategy*. For example, the *Clean Water Action Plan* (EPA, 1998a) includes a goal to improve assurance that fish and shellfish are safe to eat, and specifically calls for action on mercury. The *Study of Hazardous Air Pollutant Emissions from Electric Utility Steam Generating Units - Final Report to Congress* (EPA, 1998b) identifies hazardous air pollutant emissions from utility boilers. The report indicates that of the pollutants studied, on balance, mercury releases from coal-fired power plants are the greatest potential public health concern. The *Deposition of Air Pollutants to the Great Waters: Third Report to Congress* (EPA, 2000a) lists mercury among the 15 Great Waters "Pollutants of Concern." Finally, the EPA Program Offices and Regions, via the Mercury Task Force (MTF), have prepared the *Draft EPA Action Plan for Mercury* as part of A *Multimedia Strategy for Priority Persistent, Bioaccumulative, and Toxic Pollutants* (Federal Register, 1998). A final plan, which includes a number of near-term and longer-term regulatory and voluntary actions that EPA will undertake to address mercury, is expected in late-2000.

ORD developed the *Mercury Research Strategy* in close consultation with EPA's Program and Regional Offices and will use it to guide the development of a more detailed multi-year implementation plan in FY 2001. The *MRS*

provides strategic guidance for ORD's mercury research program over the next five years (FY2001 - 2005). It is specifically designed to target both near-term and long-term scientific research needs. In the near term, ORD plans to focus on combustion risk management. In the longer term, ORD will emphasize research that enhances the fundamental understanding of human health effects and exposure, ecological effects and exposure, non-combustion risk management, and risk communication. Mercury fate and transport research will be a focus throughout the five-year time frame of the *MRS*. The *Mercury Research Strategy* recognizes the global nature of the mercury problem and the need for addressing impacts in the United States via hemispheric transport of emissions generated by other nations. Its emphasis, however, is on domestic sources. This is in accordance with existing EPA program priorities, although priorities can change as a result of changing Agency needs.

The goal of the *MRS* will be accomplished through an applied in-house research program conducted by ORD laboratories and assessment center. Coupled with these in-house efforts, ORD's Science to Achieve Results (STAR) Grants Program conducted by the National Center for Environmental Research (NCER) will sponsor extramural research. This research will advance the fundamental understanding of important mercury and methylmercury issues. Other organizations will also be invited to address pertinent scientific and technical topics in their areas of competency. The research conducted under the *MRS* will be multi-disciplinary in nature, requiring engagement and collaboration across a host of different scientific and technical disciplines. Results from the mercury research program will provide the scientific underpinnings for any actions (*e.g.*, voluntary, regulatory) that the Agency chooses to pursue in the future to address mercury risks.

1.1.1 Exposure Route of Most Concern

The *MRS* incorporates a number of the research needs identified in the *Mercury Study Report to Congress* and emphasizes the route of exposure portrayed in Figure 1. That exposure route begins when mercury is emitted from human activities (*i.e.,* anthropogenic sources) and becomes airborne for varying periods of time. Eventually, airborne mercury is deposited on land or water where it is transformed to organic forms of mercury (*i.e.,* methylmercury[3]). This methylmercury is taken up by fish and fish eaters (*e.g.*, larger fish, eagles, otters) and eventually can find its way into humans. Once in humans at high enough concentrations, methylmercury causes neurological damage and is particularly harmful to developing fetuses and young children (*i.e.,* under 6 years of age).

While the *Mercury Research Strategy* emphasizes the fish ingestion exposure pathway, it is not the only one of interest to the Agency. Inhalation is another exposure pathway of interest, but is not addressed in the *MRS*. A national multi-agency task force is looking at the ritualistic use of mercury[4]. While the *MRS* does not focus on ritualistic use, ORD intends to work with the task force on this route of exposure, and as appropriate, will work with other Agencies and organizations on other mercury exposure routes posing human and ecological risks.

The mercury transformations that occur in air, water, and on land and methylmercury's accumulation in fish, wildlife, and humans (based on the fish ingestion exposure pathway) present a set of scientific and technical challenges for both Agency regulators and researchers. With respect to mercury research, some of the challenges include, but certainly are not limited to, developing methods that accurately characterize mercury sources and

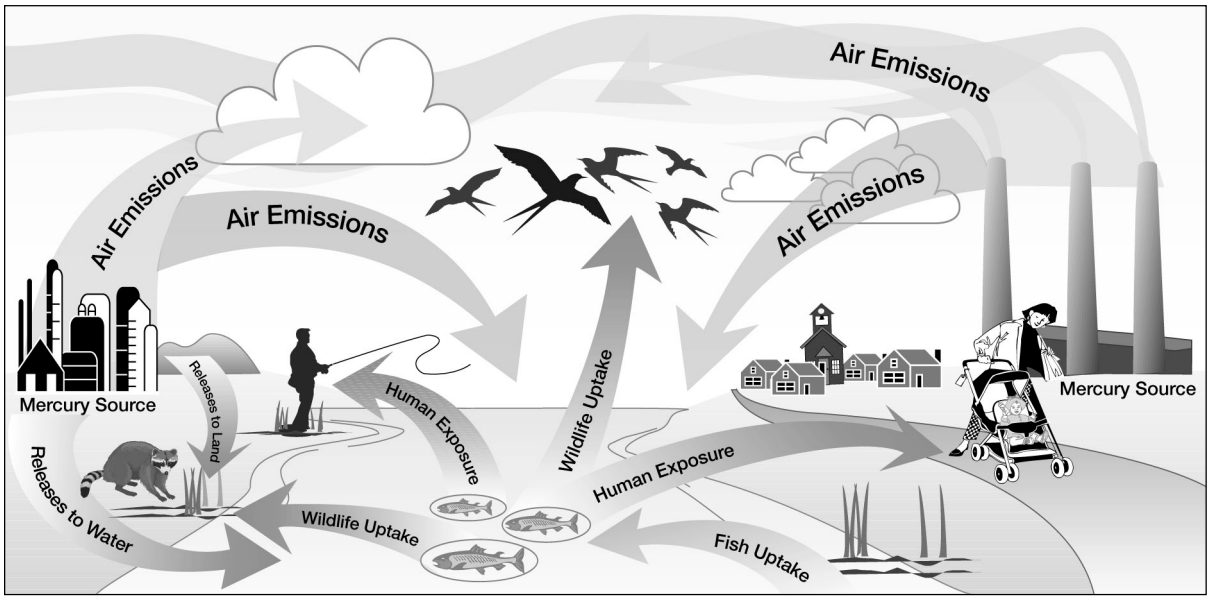

Figure 1. Mercury Fish Ingestion Exposure Pathway, the Focus of the *Mercury Research Strategy*.

the species of mercury released from those sources; understanding mercury transport and the transformations that occur in the air and water and on land; assessing mercury exposures to and effects on humans and ecosystems; and developing cost-effective ways to manage risks from mercury sources and sinks[5]. All of these challenges are addressed in the *MRS*.

1.2 INTERNATIONAL NEED TO ADDRESS MERCURY

Mercury is recognized internationally as an important pollutant warranting collaborative study and action. Virtually all countries have a common interest in mercury, since they are mercury exporters and importers via atmospheric transport. Domestic mercury reductions are only one component, albeit a very important one, for managing mercury risks in the United States. Another component is a better technical understanding of global mercury sources and circulation patterns, as well as improved estimates of global contributions to domestic ambient mercury levels. To successfully influence changes in mercury use and emissions abroad, the United States must share mercury control technology and engage in international risk management activities addressing mercury reductions. The rapid industrialization of China and other Asian nations and the resulting increased role of coal in those countries suggest an increasing emphasis on protecting the United States from international mercury sources.

Attention to monitoring and modeling (including speciation) along all U.S. borders for transboundary transport (both entering and exiting) and deposition of mercury are priorities. Preliminary studies suggest that:

- air masses from Asia reach the west coast of the United States in 3-4 days (Jaffe, et al., 1999);
- the Arctic receives 33 percent of its heavy metals deposition from industrial sources in Europe and North America (AMAP, 1997);
- trans-Atlantic transport could bring mercury species to South Florida as a consequence of dust storms in the Sahara Desert (Landis, et al., 2000).
- mercury transits to and from the United States, Canada, and Mexico (Nriagu, 1999).

EPA's long-range modeling analysis of domestic anthropogenic sources, as reported in the *Mercury Study Report to Congress*, found that there is no region of the United States where mercury deposition is not occurring. The range of deposition spans two orders of magnitude (0.5 - 50 µg per square meter per year) (EPA, 1997a). EPA is just beginning to focus on the regional, intercontinental, and global dimensions of mercury. One team of investigators has estimated that Asian sources account for about 46 percent of the anthropogenic mercury global total (Pirrone, et al., 1996). While combustion sources are a significant concern, there are uncertainties in the understanding of mercury emissions from non-combustion sources such as mercury cell chlor-alkali facilities. Globally, 200-300 factories hold approximately 50-60 million pounds of mercury and require 2-3 million pounds of new mercury annually to replenish consumption during production (Anscombe, 2000).

There is a growing appreciation of the global nature of the mercury problem and also of the need for joint action. EPA is currently exploring, with the Department of State (DOS), a variety of mechanisms and activities to elevate attention to mercury internationally. As a foundation for an international focus, the Agency now plans to develop an *International Mercury Strategy*. This international strategy will provide a framework and rationale for guiding the Agency's efforts, in concert with other agencies and the international community. It will facilitate development of global coordination and action on risk assessment and risk management for mercury. The international strategy will address how best to: (1) obtain and apply international routine emissions (including speciation) and multimedia monitoring and modeling information; (2) obtain and apply international research on exposure, effects, ecological and human risk assessment, and risk management research information; and (3) develop and implement risk management objectives in pollution prevention, capacity building, training, technology transfer and international formal deliberations, such as treaties or other mechanisms.

1.3 MERCURY RESEARCH STRATEGY ORGANIZATION

The *MRS* addresses a range of topics, including sources of mercury releases, air emission sources, human health and wildlife impacts, transport and fate of mercury in the environment, and techniques to manage risks from the largest emitting sources. It is organized as follows:

- Chapter 2.0 describes the challenges associated with mercury from source to receptor, including a discussion of mercury emissions and releases; mercury transport, transformation and fate; impacts of methylmercury on human and wildlife health; and mercury and methylmercury risk management.
- Chapter 3.0 explains why the *MRS* was developed and includes: the findings of the National Academy of Sciences (NAS) on the methylmercury reference dose (RfD); regulatory commitments on mercury by Agency Programs; voluntary efforts to prevent or minimize mercury in products, processes and wastes; and international opportunities to reduce mercury on a global scale.

- Chapter 4.0 summarizes the research efforts being performed by public and private organizations (*e.g.* federal, state, and local governments; academic institutions; the private sector) as well as international research efforts that will complement the research areas discussed in the *MRS*.
- Chapter 5.0 presents the key scientific questions and the strategic directions for EPA's mercury research program over the next five years, and identifies EPA's research priorities. It also provides detailed descriptions of the research needs to be addressed under each of the six key scientific questions.
- Chapter 6.0 identifies issues beyond research that deserve attention and are supportive of the *Mercury Research Strategy*. It also describes future opportunities for engagement and partnering with a variety of stakeholders (*e.g.*, regulated entities, environmental groups, community decision-makers at all levels, the general public, international entities).
- Chapter 7.0 contains the set of references cited in the *Mercury Research Strategy*.
- Appendix A includes a summary of nine transport and fate grants awarded in FY 1999 as part of ORD's STAR Grants Program.

1. The *Mercury Study Report to Congress* identified methylmercury as the mercury chemical species of greatest environmental concern. Volume V of the Mercury Study Report to Congress and the toxicology profile on mercury developed by the Agency for Toxic Substances and Disease Registry (ATSDR, 1999) provide more information on the adverse human health effects of inorganic mercury.

2. For the purposes of the *Mercury Research Strategy*, releases include all forms of mercury entering the environment (i.e., air, water, deposited on land). The term emissions deals with mercury entering the air. The term effluents deals with waterborne mercury entering water or depositing on land.

3. For the purposes of the *Mercury Research Strategy*, "mercury" refers to all forms of the element prior to methylation. Adverse human and ecological effects of the element occur from methylmercury exposures reflecting the chemical species bioconcentrated in the aquatic food web. Consequently, the term "methylmercury" is used when describing mercury in fish and the adverse health effects of mercury via the fish ingestion exposure pathway. When describing Agency programs, efforts, and documents the generic term "mercury" is used for all chemical species of mercury.

4. The task force is co-led by EPA's Office of Emergency and Remedial Response (OERR) and the Agency for Toxic Substances and Disease Registry (ATSDR). In the near term, the task force plans to convene an external expert panel to address the issue of ritualistic use, develop a tool kit to help local and state governments respond to ritualistic use problems, sponsor a pilot investigation to better understand the scope and nature of the exposure and prepare a national strategy on how to deal with the issue of ritualistic use.

5. For the purposes of the *Mercury Research Strategy*, sources are generally locations (e.g., points, areas) of mercury releases, including emissions, from human activities and sinks are locations of mercury deposition. It is recognized that sources may also be natural mercury sources and sources that re-emitted mercury. In some cases, sinks may act as re-emission sources, depending upon their location and the form of the mercury present in the sink.

2.0 PROBLEM DESCRIPTION

2.1 WHY MERCURY POSES A RISK

The amount of mercury released from both natural and anthropogenic sources is difficult to quantify. Studies by Nriagu and Pacyna (1988) estimated global natural emissions at 3000 tons per year and the median for global emissions from human activities at 3560 tons per year (1983 basis). A more recent critical review by Jackson (1997) estimated that 2000 tons of mercury are emitted each year from natural sources, while 4000 tons of mercury are emitted each year from sources attributed to human activities (*e.g.*, combustion of fossil fuel and solid waste). An overview of global atmospheric emissions prepared by Schroeder and Munthe (1998) cited a number of other natural and anthropogenic source estimates along with the scientific uncertainties associated with estimates for both.

When airborne mercury is deposited on land or in water, biological transformations can occur that yield methylmercury. In its methylated form, mercury accumulates most efficiently in the aquatic food web resulting in risks to both humans and ecosystems (EPA, 1997a). Nearly all of the mercury that accumulates in fish is methylmercury. In lakes, rivers, and reservoirs, methylmercury is taken up by fish, resulting in significant increases in its concentration in fish tissue (*i.e.,* bioaccumulation). In some instances, the concentrations of methylmercury in fish may be several orders of magnitude greater than the concentrations in the surrounding water or sediment. Inorganic mercury, which is less efficiently absorbed and more readily eliminated from the body than methylmercury, tends not to bioaccumulate.

Human and wildlife exposure to methylmercury occurs almost exclusively through fish consumption. Fish eaters at the top of the aquatic food web generally exhibit higher methylmercury concentrations than those lower in the food web. The decision to focus on this exposure pathway in the *Mercury Research Strategy* is supported by modeling results from the *Mercury Study Report to Congress* (Volume IV: An Assessment of Exposure to Mercury in the United States). That modeling effort demonstrated that fish consumption poses the greatest risks to human health and wildlife. The impacts from urban and agricultural modeling were not of a comparable concern.

2.2 IMPACTS OF METHYLMERCURY ON HUMAN HEALTH AND WILDLIFE

Methylmercury is known to have toxic effects in humans, causing permanent damage to the brain and kidneys. The developing nervous system (*e.g.,* human fetuses, bird embryos) is particularly sensitive to methylmercury exposures. Human epidemics of methylmercury poisoning (*e.g.,* Japan, Iraq) have established its toxicity to the nervous system (EPA, 1997a).

> There are extensive data on the effects of methylmercury on the development of the brain (neurodevelopmental effects) in humans and animals. The most severe effects reported in humans were seen following high dose poisoning episodes in Japan and Iraq. Effects included mental retardation, cerebral palsy, deafness, blindness and dysarthria in individuals who were exposed in utero and sensory and motor impairment in exposed adults. Chronic, low-dose prenatal methylmercury exposure from maternal consumption of fish has been associated with more subtle end points of neurotoxicity in children. Those end points include poor performance on neurobehavioral tests, particularly on tests of attention, fine-motor function, language, visual-spatial abilities (e.g., drawing), and verbal memory.
>
> Excerpt from the Executive Summary of the Toxicological Effects of Methylmercury, National Research Council 2000. http://books.nap.edu/books/0309071402/html/index.html

2.2.1 Human Health Impacts

Perhaps the most well known incident of mercury poisoning involved the consumption of methylmercury-contaminated seafood from Minamata Bay in Japan during the 1950s. In that case, mercury was used as a catalyst in an acetaldehyde production plant and was released into the Bay. The methylmercury poisoning involved the death and permanent disability of a number of individuals. The pathway of exposure being addressed in the *Mercury Research Strategy* is far more subtle. It involves the emission of low concentrations of mercury, mainly from combustion sources. These emissions lead to the build-up of methylmercury in water bodies and fish tissue over time. It is important to stress that the most likely individuals being exposed to a high level of methylmercury are consumers of large quantities of fish (*e.g.,* subsistence fishers). Pregnant women (maternal/fetal pair) and young children are particularly sensitive to exposures of high levels of mercury.

As illustrated in Figure 2, forty states have some form of mercury fish advisories for their water bodies. Statewide advisories for mercury occur consistently across the Northeastern states; Gulf Coast states have advisories in all coastal waters. In Canada, 97 percent of fish advisories are attributable to mercury. Mercury is the major reason for fish advisories, and there is an increasing trend in the

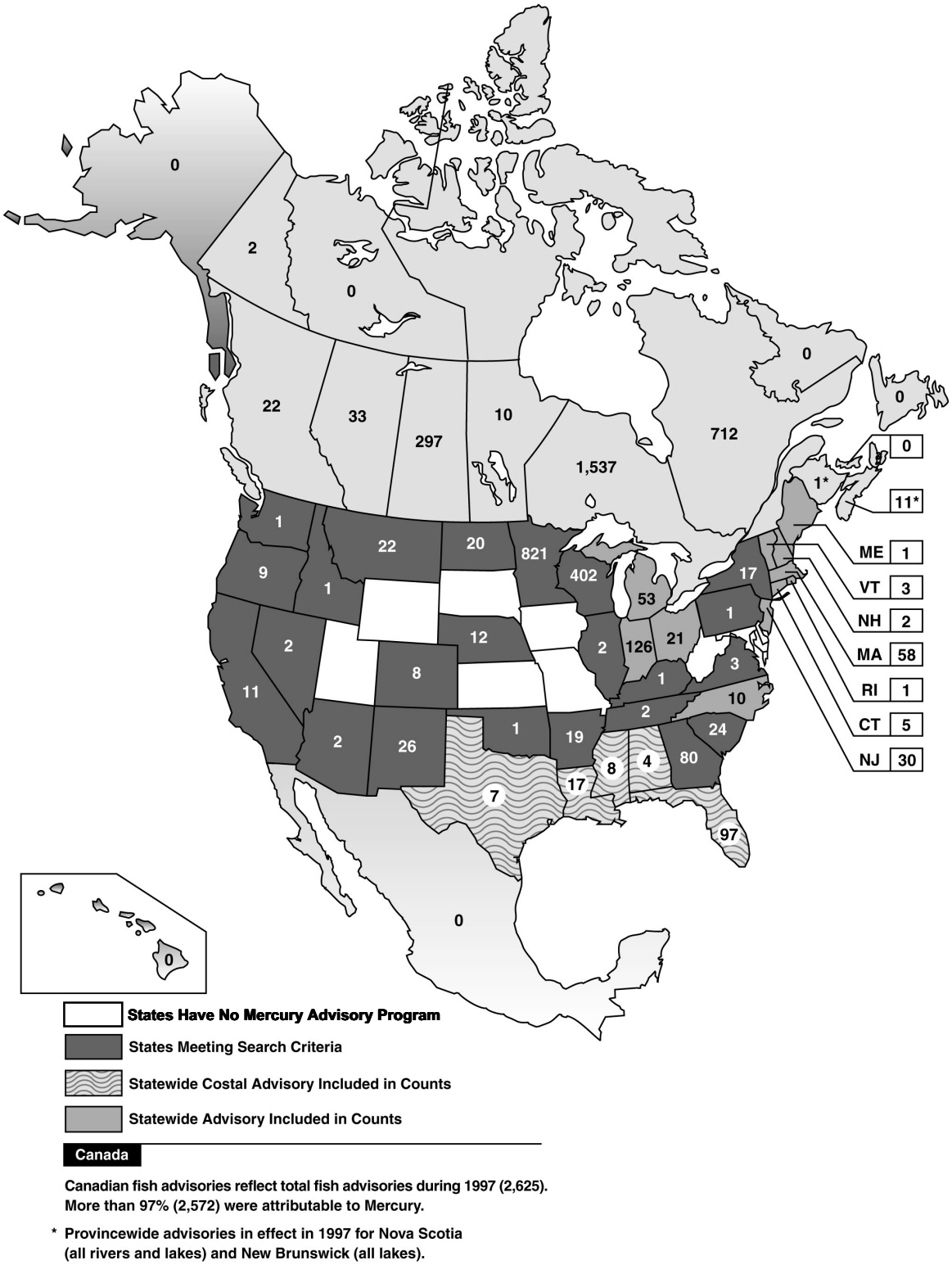

Figure 2. Mercury-based Fish Consumption Advisories for North America (EPA, 1999a; EPA, 1999c).

number of advisories due to its presence in the nation's waters. Based on an analysis of dietary surveys, the *Mercury Study Report to Congress* (EPA, 1997a) risk assessment concluded that typical fish consumers in the United States were not in danger of ingesting harmful levels of methylmercury. This is a reflection of the relatively low amounts of fish consumed by the typical U.S. citizen.

Based on the same analysis of United States dietary survey data, the risk assessment estimated the percentage of people from different populations who consume methylmercury in excess of the Reference Dose (RfD)(EPA, 1997a)[1]. Among white/non-Hispanic populations, the fraction above the RfD was 9.0 percent, among black/non-Hispanics, 12.7 percent, and among persons of Asian/Pacific Islander ethnicity, Native American tribal members, and non-Mexican Hispanics (*e.g.,* persons from Puerto Rico and other Caribbean islands), 16.6 percent. Among women of childbearing age (*i.e.,* 15 through 44 years), 7 percent of the more than 58 million women in the group (*i.e.,* more than 4 million women) are exposed to methylmercury from fish at levels in excess of the RfD, using month-long exposures as the basis for calculation.

Depending on the methylmercury concentration in the fish, women may be putting their fetuses at risk to the subtle neurological and developmental effects associated with methylmercury exposure. In addition to women of childbearing age and their fetuses, populations of concern include young children (whose nervous systems continue to develop after birth). Young children exposed to methylmercury are of particular concern (EPA, 1997a), especially when they are members of a group who depend heavily on fish and fish-eating mammals as part of their diets (*e.g.,* some native groups that are subsistence fishers).

2.2.2 Wildlife Impacts

> Concentrations of mercury in the tissues of wildlife species have been reported at levels associated with adverse effects in laboratory studies of the same species. However, field data are insufficient to conclude whether piscivorous wading birds or mammals have suffered adverse effects due to airborne mercury emissions. Modeling analyses suggest that it is probable that individuals of some highly exposed wildlife subpopulation are experiencing adverse effects due to airborne mercury.
>
> Excerpt from the Executive Summary of the *Mercury Study Report to Congress*, Volume I, December 1997. http://www.epa.gov/oar/mercury.htm

The impacts on wildlife from exposures to methylmercury are described in detail in the *Mercury Study Report to Congress* (EPA, 1997a). For purposes of this discussion, wildlife includes fish, birds (*e.g.,* loons, ducks, eagles), and fur-bearing mammals (*e.g.,* otters, mink, panthers). All are susceptible to adverse methylmercury health effects. Marine mammals such as seals, walruses, dolphins and whales are also susceptible to methylmercury. Trace levels of mercury have been found in the liver of seals, porpoises and dolphins (Law, et al., 1991). The exposure pathway in aquatic systems indicates that birds and small mammals that feed primarily on fish and those that prey on these fish eaters will be at the greatest risk of toxic effects from methyl-mercury. An important aspect of these effects are the bioaccumulation of methylmercury by less complex organisms (*e.g.,* plankton, clams, crayfish,) and then their consumption by fish and small mammals. Direct uptake of methylmercury in the water column is also a pathway of exposure. These species can actually provide an early warning of mercury contamination via indications of neurological damage and reduced reproductive levels.

Mercury toxicity in fish is variable depending on a number of factors. These include fish characteristics (*e.g.,* species, life stage, age, size), environmental factors (*e.g.,* temperature, salinity, dissolved oxygen content, water hardness, other chemicals), and the form of mercury available (EPA, 1997a). The effects of methylmercury on early life stages of fish present more acute problems such as death, reduced reproduction, impaired growth and development, behavioral abnormalities, altered blood chemistry, reduced feeding rates and predatory success, and effects on oxygen exchange. Some signs of acute mercury poisoning include increased mucous secretion and respiration rate, loss of equilibrium, and sluggishness. Chronic poisoning is represented by emaciation, brain lesions, cataracts, and an inability to capture food. Evidence suggests that effects can be detected in water concentrations between 0.1 and 1.0 micrograms per liter for some species.

As summarized in the *Mercury Study Report to Congress* (EPA, 1997a), symptoms of mercury poisoning in birds include: muscular incoordination, falling, slowness, fluffed feathers, calmness, withdrawal, hyperactivity, hypoactivity, and drooping eyelids. Liver and kidney damage, neurobehavioral effects, reduced food consumption, weight loss, spinal cord damage, enzyme system effects, reduced cardiovascular function, and impaired growth and development are several of the indicators of sublethal effects of mercury in birds. Tissue mercury concentrations that are associated with toxicity in birds are similar despite differences in species, dietary exposure level, and length of time necessary to produce the effect. Neurological signs are generally associated with brain mercury concentrations of 15 micrograms per gram (wet weight) and 30 micrograms per gram in the liver and kidneys. With respect to hatchlings, mortality was observed in ducklings at 3 to 7 micrograms per gram (wet weight), at 2 to 3 micrograms per gram in loon eggs, and at 3.6 micrograms per gram in tern eggs. No effects were seen in herring gull hatchlings although the eggs contained approximately 10 micrograms per gram of mercury.

The *Mercury Study Report to Congress* identified the mink and otter as examples of fur-bearing mammals with increased risk from methylmercury exposure (EPA, 1997a). This was for exposures related to direct discharges of mercury to water bodies. The impacts of mercury on these mammals are less clear than for either fish or birds. This may be a direct reflection of the limited number of studies conducted on fur-bearing mammals and, in some cases, the confounding effects of other stressors. These stressors, cited for the endangered Florida panther, include habitat fragmentation, inbreeding, and feminization by endocrine disrupting compounds. With respect to the Florida panther, relatively high levels of mercury (0.005 to 20.0 micrograms per gram) have been measured in archived liver samples of dead animals. In another case, one death was attributed to mercury poisoning with mercury measured at 100 micrograms per gram in the liver and 130 micrograms per gram in the hair.

Based on the investigations reported in the *Mercury Study Report to Congress* (EPA, 1997a), causal links with airborne mercury deposition have not been established, but may contribute to population effects in some birds and fur-bearing animals, including the Florida Panther. The effect of mercury from point sources on limited wildlife populations, however, has been demonstrated. Tissue residues from these studies provide a basis for evaluating risks to other wildlife populations. Overall, wildlife *(e.g.,* fish, birds, fur-bearing mammals) appear to be more susceptible to mercury effects when they are located in ecosystems that experience the following: (1) high levels of atmospheric deposition, (2) surface waters already impacted by acid deposition, (3) characteristics other than low pH that result in high levels of mercury bioaccumulation in aquatic biota, and (4) species that experience high levels of exposure.

2.3 MERCURY USES AND RELEASES

2.3.1 Uses

Mercury has been widely used in industrial applications because of its unique properties. It conducts electricity, responds to temperature and pressure changes, and forms alloys with almost all metals. In the electrical industry, mercury is used in fluorescent lamps, as part of wiring devices, and with instruments that measure temperature and pressure. It is also a component of dental amalgams used in restoring teeth. In addition to its use in specific products, mercury is used in numerous industrial processes. The largest manufacturing use of mercury in the United States is associated with the production of chlorine and caustic soda by mercury-cell chlor-alkali plants. Mercury is also used in amalgamation with other metals (*e.g.,* gold) and as an antifungal agent in wood preserving (EPA, 1997a).

2.3.2 Releases

The most significant releases of mercury to the environment in the United States are emissions to the atmosphere. These emissions can be characterized as releases by human activities (*i.e.,* anthropogenic), releases from geologically bound mercury through natural processes, and releases through mass transfer to the atmosphere by biologic and geologic processes from previously deposited mercury (*i.e.,* re-emitted) (EPA, 1997a)[2]. The *Mercury Study Report to Congress* presents an inventory (based on 1994/1995 data) of anthropogenic mercury air emissions in the United States (See Table 1). This table presents the percentage of anthropogenic emissions attributable to each major source.

Table 1. Summary of Major Sources of Anthropogenic Mercury Air Emissions (EPA, 1997a).

Source	Percent
Coal-fired electric utility boilers	32
Municipal waste combustors	18
Coal- and oil-fired commercial/industrial boilers	18
Medical waste incinerators	10
Chlor-alkali plants	4
Portland cement plants	3
Oil-fired residential boilers	2
Other sources of mercury	13

Anthropogenic mercury sources within the United States emit approximately 158 tons of mercury per year (EPA, 1997a)[3]. The source categories presented in the table each constitute more than one percent of the total amount of mercury emitted to the atmosphere from human activities. The greatest emissions of anthropogenic mercury to the environment are from combustion of fuel that contains trace amounts of mercury. Emissions also come from industrial processes that use mercury, and disposal (especially by incineration) of products that contain mercury either as an intentional constituent or as an impurity.

Mercury-bearing wastes are generated from manufacturing processes and the disposal of consumer products. In 1995 an estimated 245 tons of mercury were discarded in municipal waste streams (EPA, 1997a). Most of this waste was either incinerated or placed in landfills. Industrial hazardous wastes with high mercury concentrations are currently incinerated or retorted. Retorting involves the heating of mercury-containing wastes with the mercury converting to a vapor. The mercury vapor is then captured and condensed back to its metallic form. The intentional use of mercury in commercial products in the United States has declined by more than 75 percent from 1988 to 1996 (EPA, 1997a). This reduction is largely due to the private sector's efforts to eliminate the use of mercury in products

and processes when replacements can be found. Along with this commercial use reduction, an increase in the recycling and recovery of mercury has resulted in a supply of the metal that now exceeds domestic demand.

In addition to air emissions and land disposal, mercury is released in other ways, including discharges from industrial sources and waste sites and releases of methylmercury from sediments to water bodies. Release of mercury in water discharges is believed small when compared to atmospheric emissions, but it can have significant local effects. Mercury discharges to surface waters from abandoned gold and mercury mines in the western United States may well be the cause of fish advisories for methylmercury in a number of streams and lakes. An example is the contamination of Clear Lake in California by the Sulphur Bank Mercury Mine Superfund Site. An international example of mercury pollution from an industrial source exists in Natal, South Africa, where the Thor Chemical Plant houses large quantities of mercury wastes that have leaked/leached to the nearby environment and groundwater. Releases of methylmercury from sediments have not been well quantified, but high concentrations of methylmercury in sediments often coincide with high concentrations of methylmercury in fish tissue (EPA, 1999a).

Modeling conducted as part of the *Mercury Study Report to Congress* (EPA, 1997a) estimated that approximately one-third of the United States anthropogenic mercury emissions (about 52 tons) are deposited through wet and dry deposition within the contiguous 48 States. The remaining two-thirds is transported outside the continental U.S. and enters the global mercury cycle. It is estimated that an additional 35 tons per year are deposited in the United States from the global cycle (*i.e.,* anthropogenic, natural, and re-emitted sources) (EPA, 1997a). As a consequence of mercury emission controls on a number of sources, anthropogenic mercury emissions in the United States will most likely decline over the next several years. According to Pirrone, et al., (1996), releases from human activities globally will increase mercury deposition in the United States unless reductions also occur in other countries. The role that emissions from natural and re-emitted sources play in assessing reductions to mercury is a complicating factor. These emissions must be taken into consideration in any estimates or documentation of total mercury reductions to the environment over the longer term.

2.4 MERCURY TRANSPORT, TRANSFORMATION, AND FATE

2.4.1 Transport

The air transport and deposition patterns in the United States for mercury emissions depend on various factors, including the form of mercury emitted, the location of the emissions source, the stack height of the source, the topography near the source, and the prevailing air circulation patterns. For example, anthropogenic point sources (*e.g.,* coal-fired electric utility boilers, municipal waste combustors) emit primarily elemental mercury vapor (Hg^0), gas-phase ionic mercury (Hg^{+2}), and lesser amounts of particulate-bound mercury (Hg_p). The chemical and physical properties of these different mercury forms influence their behavior in the environment and their significance as contaminants that have local, regional and global scale impacts.

Local scale impacts result from deposition within a 30-mile radius of an emissions source. For example, a source emitting primarily Hg^{+2} can be expected to have a relatively high percentage of mercury deposited within the 30-mile radius via wet deposition (EPA, 1997a).

Regional scale impacts result from either wet or dry deposition associated with long-range transport of emissions over hundreds of miles dispersed across wide areas. The highest deposition rates in the United States are predicted to occur in the southern Great Lakes and Ohio River Valley, the Northeast and scattered areas in the Southeastern United States (EPA, 1997a).

Global scale impacts result from Hg^0 emissions that become part of the global emissions pool, where they can remain for a year or more before wet or dry deposition, on land or water. For example, recent studies indicate that in Arctic air, elemental mercury vapor may be oxidized resulting in increased mercury deposition (Schroeder and Munthe, 1998).

2.4.2 Transformation and Fate

Anthropogenic mercury that is released directly to land or water bodies, or is deposited on them from the atmosphere, undergoes transformations that are not fully understood. These transformations convert some of the mercury to methylmercury. Not only is methylmercury much more toxic to humans and wildlife than inorganic mercury, but it is also more likely to bioaccumulate in fish tissue. This ability to bioaccumulate results in food chain impacts yielding higher concentrations of methylmercury in both humans and wildlife. The amount of mercury transformed to methylmercury varies greatly from one water body to another. According to Krabbenhoft, et al., (1999), there are a number of factors that influence methylmercury production beyond mercury loading. These are environmental setting (*e.g.*, climate, geology, land use, land cover), water chemistry, and wetland density with the latter being the most important basin-scale factor controlling methylmercury production.

2.5 MERCURY AND METHYLMERCURY RISK MANAGEMENT

2.5.1 Risk Management

Reducing risks from methylmercury is difficult because of the wide variety of sources that contribute mercury to the environment. Managing emissions and other releases of mercury requires a variety of approaches ranging from product substitution to end-of-pipe treatment. Some actions, such as eliminating mercury used in paints and batteries and controlling flue gas emissions from municipal waste combustion units and medical waste incinerators, are part of the technological options already used to reduce releases and emissions. Other options, such as removing mercury-containing products from waste streams (separation), coal cleaning, fuel switching, advanced mercury sorbents, sediment remediation methods, substitutes for mercury used in electronic switches and thermometers, and conversion of chlor-alkali plants from a mercury electrolytic cell to a membrane cell process, are available or under development.

Cooperative research between the public and private sectors is underway (*e.g.,* coal-fired utilities, mercury chlor-alkali production) to further develop management options, test and evaluate innovative solutions, refine or develop new data on their costs, and determine the benefits of combining various risk management approaches. Life-cycle tools are in various stages of development to evaluate how a mix of options can best be deployed to maximize reduction of risks to humans and wildlife at minimal cost. Development and evaluation of process changes, product substitutions, and innovative technologies will provide additional ways to address mercury. Finally, as the demand for mercury continues to decrease, issues involving mercury retirement will also come to the fore.

2.5.2 Risk Communication

Communicating human health and ecological risks is an important component of any regulatory or voluntary Agency action and a vital part of effective risk management. Research can contribute to a methylmercury risk communication program in several ways that will assist EPA, state and local officials, and the public. There is a need to synchronize and standardize the fish consumption advisory messages for the numerous states in which they are issued. The criteria or standards each state uses to make fish advisory decisions are an essential element of any such effort. This research can be facilitated with a concerted and collaborative effort on the part of the federal agencies (*i.e.,* EPA, ATSDR, Food and Drug Administration [FDA]) that set various action levels for methylmercury in fish.

An improved understanding of exposure patterns (*e.g.,* amount of fish consumed, types of fish consumed, frequency of consumption) will assist in targeting both populations and the messages those populations receive. Research is needed on ways that people, in particular the populations most exposed to mercury and methylmercury risks, use information to make informed decisions. This will be particularly challenging since the most-exposed populations (*i.e.,* fetuses and young children) are not able to understand risk messages. The groups to reach will be their parents and other responsible adults.

1. A reference dose (RfD) is defined as an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive populations) that is likely to be without an appreciable risk of deleterious effects during a lifetime. (EPA, 1997a). At the RfD or below, exposures are expected to be safe. The risk associated with exposures above the RfD is uncertain, but risk increases as exposures to methylmercury increase.

2. With respect to this last category, a large portion of the deposited mercury is the result of past anthropogenic releases as well as releases from natural sources that heretofore have been sequestered (e.g., arctic tundra, ice sheets, oceans and wetlands) (Lindberg, et al., 1998).

3. According to the Mercury Study Report to Congress, "[t]he current state of knowledge of mercury emissions . . . does not allow for an accurate assessment of either natural or re-emitted mercury emissions." It is altogether likely that natural and re-emitted mercury emissions associated with contaminated soils and water bodies within the United States could add significantly to this value (EPA, 1997a).

3.0 REGULATORY ACTIONS AND OTHER FACTORS THAT INFLUENCE MERCURY RESEARCH PRIORITIES

3.1 NATIONAL ACADEMY OF SCIENCES REPORT

In the FY 1999 conference report for EPA's appropriation (U.S. House of Representatives, 1998), Congress directed the Agency to ". . . enter into a contract . . . with the National Academy of Sciences (NAS) to perform a comprehensive review of mercury health research . . . ." As part of that study, NAS was to make recommendations on a scientifically appropriate reference dose (RfD) for mercury exposure. Methylmercury was specifically targeted and the goal was to resolve varying interpretations of methylmercury health effects data. EPA was directed to delay any decisions to regulate mercury until the NAS findings had been published. The findings of the NAS study (NRC, 2000) were presented on July 11, 2000. They support EPA's current RfD of 0.1 micrograms per kilogram body weight per day as a scientifically justified level to protect human health. The study further affirmed that the fetus is the most vulnerable to methylmercury effects and that the developing nervous system is the critical endpoint for risk calculations.

The NAS report evaluated data on methylmercury effects from the Seychelles and Faroe Islands studies, as well as recently published data from a New Zealand study. An integrative analysis of all three studies was performed and some of the Faroe Islands study data were extensively re-analyzed. Using these analyses, NAS recommended that the data from the Faroe Islands study (rather than the data from an older Iraqi study) be used as the basis for the RfD (NRC, 2000). The Iraqi study, involving poisoning through the consumption of mercury-treated wheat, was used to establish the EPA RfD in 1994 (EPA, 1997a). The NAS study also recommended that a safety factor of 10 was needed to address any scientific uncertainties that remained. With the NAS study completed and supportive of the Agency's RfD, EPA is now faced with making decisions on regulating mercury and methylmercury in the environment.

3.2 REGULATORY AND OTHER DOMESTIC COMMITMENTS

Numerous Program Office commitments related to mercury must be addressed over the next five to ten years (Table 2). This section presents a brief summary of existing and proposed regulations and initiatives related to mercury. The data collected in preparation for rule making or submitted in compliance with regulatory requirements or initiatives will help guide the *Mercury Research Strategy*. Likewise, the information collected as part of the *MRS* research effort will help inform the rule making process. This exchange of mercury-related information will improve the Agency's understanding of mercury use in specific industries, its impact on human health and wildlife, and its fate and transport. Descriptions of existing and proposed mercury-related regulations and initiatives are summarized in Table 2 and described in this section.

3.2.1 Regulatory Activities

Mercury Controls for Utilities: One of the most important commitments is the Office of Air and Radiation's (OAR's) implementation of the 1990 Clean Air Act, as amended. As required by section 112(n) of the Act, EPA is faced with regulating hazardous air pollutants (HAPs), including mercury, from coal-fired electric utility steam generating units. A positive determination means that EPA is required to propose regulations by December 15, 2003 and promulgate final regulations by December 15, 2004. Full compliance by the utility industry would be expected by December 15, 2007. Such a regulatory program requires the development of technical information and data on the cost and performance of options (*e.g.*, flue gas treatment, coal cleaning) to reduce utility boiler emissions.

MACT Rules for Chlorine Production and Municipal Solid Waste Landfills: Under section 112 of the Clean Air Act, EPA is required to develop national emission standards based on maximum achievable control technologies (MACT) for HAPs (which includes mercury) listed in section 112 (b) for various source categories such as chlorine production, municipal landfills, and industrial/commercial/institutional boilers. Generally, sources are required to be in full compliance with these rules three years after promulgation of the final rule.

Chlorine Production - OAR is developing a rule that will limit mercury emissions from plants that produce chlorine using the mercury cell method. EPA plans to issue a proposed rule by November 2000 and a final rule by November 2001. The rule will be based on best available control technologies and stringent management practices.

Municipal Solid Waste Landfills - OAR is developing a rule that will address emissions of HAPs from municipal solid waste landfills using the MACT approach. EPA plans to issue a proposed rule by November 2000 and a final rule by September 2001. This source category includes contiguous geographical space/facilities receiving household waste, and other types of Resource Conservation and Recovery Act (RCRA) Subtitle D waste, such as commercial solid waste, non-hazardous sludge, conditionally exempt small quantity generator waste and industrial solid waste.

Table 2. EPA Regulatory Activities Affecting Mercury Releases to the Environment.

Program Office/Region	Regulatory Activities	Fiscal Year Target Date
Office of Air and Radiation		
Regulatory Determination for Electric Utilities	Promulgate Rule on Mercury Controls for Utilities	2005
	Attain Full Compliance by Utilities Industry	2008
Maximum Achievable Control Technology Standards 1. Chlor-Alkali Facilities 2. Landfills	Promulgate MACT Proposals for Chlorine Production, and Municipal Landfills	2001
	Attain Full Compliance with MACT Proposals for Chlorine Production and Municipal Landfills	2004
Integrated Urban Air Toxics Strategy	Develop Initial Urban Area Source Standards	2002
	Complete Urban Area Source Standards	2004
	Attain Full Compliance with Urban Area Source Standards	2009
Office of Water		
Revisions to Mercury Water Quality Criteria	Revise Human Health Water Quality Criterion for Mercury (TMDLs)	2001
Office of Solid Waste and Emergency Response		
Land Disposal Restrictions on Mercury	Propose Land Disposal Restriction for Mercury-bearing Hazardous Wastes	2001
MACT Standards	Propose Phase 2 MACT Rule for Hazardous Waste Combustion	2001
	Propose MACT Standards for Boilers and Industrial Furnaces Burning Hazardous Wastes	2001

Urban Area Source Standards: The Integrated Urban Air Toxics Strategy (Federal Register, 1999) is an important part of EPA's national air toxics program. Under the national air toxics program, EPA has and will continue to develop a number of national standards for stationary and mobile sources to improve air quality in urban and rural areas. The Urban Air Toxics Strategy complements the existing national efforts by focusing on further reductions in air toxics emissions in urban areas. Emissions standards are currently under development or have already been issued for sixteen categories (Federal Register, 1992). The other thirteen area source categories are new to the EPA's Source Category list . EPA anticipates promulgating emissions standards for these additional categories in FY 2004. Full attainment will be in FY 2009.

Human Health Water Quality Criterion for Mercury and Total Maximum Daily Loads (TMDLs): The Office of Water (OW) is developing a revised human health water-quality criterion for mercury. This revised human health criterion is scheduled for release in FY 2001. In the longer term, there is a programmatic need for a wildlife criterion which would protect birds and terrestrial animals from the effects of mercury. OW is conducting two pilot projects for water bodies impaired by airborne deposition of mercury. If the methodology is successfully demonstrated, TMDLs[1] will be developed, mostly by the states, for all such water bodies.

Land Disposal Restrictions for Mercury-bearing Hazardous Wastes: The Office of Solid Waste and Emergency Response (OSWER) is re-evaluating land disposal restrictions on mercury to consider alternatives to mercury recovery and incineration. EPA is considering publication of a proposed rule to revise the 40 CFR Part 268 Land Disposal Restrictions treatment standards applicable to

mercury containing wastes. The revisions under consideration by the Agency will involve a comprehensive re-evaluation of waste treatment standards. A proposed rule is scheduled for FY 2001.

Phase 2 MACT Rule for Hazardous Waste Combustion: OSWER is planning to issue a proposal establishing MACT standards for emissions of HAPs, including mercury, from boilers and industrial furnaces which burn hazardous waste. This rule follows on the Phase 1 hazardous waste combustion MACT rule which set standards for incinerators, cement kilns, and lightweight aggregate kilns which burn hazardous waste. A schedule for the proposed rule has not been established but could occur in FY 2001.

MACT Standards for Boilers and Industrial Furnaces Burning Hazardous Wastes: EPA regulates air emissions from hazardous waste combustors and boilers and industrial furnaces (BIFs) under RCRA. The Office of Solid Waste (OSW) is currently developing MACT standards for hazardous-waste-fired industrial, commercial, and institutional boilers and two more types of industrial furnaces -- halogen acid and sulfuric acid recovery for FY 2001.

3.2.2 Special Initiatives

Special Agency initiatives and activities that support the development of the *Mercury Research Strategy* are described below.

Persistent, Bioaccumulative Toxics Initiative: EPA is committing, through the Persistent, Bioaccumulative, Toxics (PBT) Initiative to create an enduring cross-office program addressing the multimedia issues associated with priority PBT pollutants. Mercury was identified as a priority PBT, and the Agency convened the Mercury Task Force (MTF) to develop a Mercury Action Plan. The cross-agency work group that developed this action plan is continuing to look for opportunities to address mercury through a more integrated, multimedia approach.

The Great Lakes Binational Toxics Strategy: The Great Lakes National Program Office (GLNPO) is undertaking voluntary efforts to remove mercury from wastes, products, and processes, with a goal of a 50 percent reduction by the mid-2000s (EPA, 1997c). This is a joint undertaking between the United States and Canada and addresses not only mercury, but eleven other PBTs.

Hazardous Waste Reduction Voluntary Program: The Office of Solid Waste and Emergency Response (OSWER) is undertaking a voluntary effort to reduce the volume and content of PBTs (including mercury) in hazardous wastes by 50 percent before the end of FY 2005.

In all cases, these important Agency priorities benefit from ORD research, both in terms of the assessment of mercury risks to humans and wildlife and the characterization and management of risks from mercury sources.

3.2.3 International Activities

A number of bilateral and multilateral programs offer the United States an opportunity to promote and engage in cooperative mercury efforts. These international activities allow all nations to better understand and ultimately reduce the risks of mercury and methylmercury exposures (Table 3). While some opportunities are voluntary and others entail legally binding commitments, EPA's involvement in international efforts is conducted within the context of its existing statutory authority, especially with respect to the Clean Air Act, as amended. Rather than being driven by, or reacting to, international initiatives on mercury, the Agency is trying to influence them proactively.

The United Nations Economic Commission for Europe (UNECE), Convention on Long-Range Transboundary Air Pollution (LRTAP) for Heavy Metals (UNECE, 1998): In February 1998, the LRTAP Parties (47 member countries, including the U.S., all in the Northern hemisphere) concluded negotiations on a legally binding protocol on mercury and other heavy metals. The protocol includes obligations to control mercury emissions from stationary sources and to establish, update, and report mercury emission inventories. It also contains obligatory and voluntary provisions regarding the use of mercury in products.

The U.S. and 35 other LRTAP Parties signed the Heavy Metals protocol in June 1998, agreeing in principle to comply with the protocol even before it formally entered into force. As of July 2000 six countries had ratified the protocol; ten more ratifications are required for the protocol to enter into force. The U.S. is in the process of completing the steps required for ratification. Best Available Technology (BAT) standards for new and existing stationary sources must be applied two and eight years, respectively, after the protocol is in force. In addition, EPA will submit reports on its domestic inventory updates and other matters by late 2000 and annually thereafter.

The Arctic Environmental Protection Strategy (AEPS) (Arctic Council, 2000): The AEPS, ratified in 1991 by the eight Arctic nations, is implemented through five working groups, two of which are most pertinent to mercury: the Arctic Monitoring and Assessment Program (AMAP) and the Protection of the Arctic Marine Environment (PAME). AMAP is responsible for monitoring the levels and assessing the effects of selected anthropogenic pollutants in all compartments of the Arctic. AMAP teams are collecting data on sources transport, transformation, and effects of persistent organic pollutants and heavy metals. Mercury was designated by the international heavy metals team to be the priority metal for AMAP Phase II: Trends and Effects 1998-2002.

Table 3. International Mercury Activities that Support the Development of the *Mercury Research Strategy*.

Program Office/Region	Multi-National Provisions	Target Date
Office of Air and Radiation		
UNECE LRTAP Convention, Heavy Metals Protocol	Apply BAT to New Stationary Sources by 2 Years after Entry into Force of Protocol	Upon Promulgation of MACT standard
	Apply BAT to Existing Stationary Sources by 8 Years after Entry into Force of Protocol	Upon Promulgation of MACT standard
Office of Air and Radiation & Office of Research and Development		
UNECE LRTAP Convention, Heavy Metals Protocol	Submit Domestic Emissions Inventory Updates and Research Results to Support Annual Assessment of Protocol Compliance Results	2000 and annually thereafter
Office of International Activities, Office of Research and Development, & Region 10		
Arctic Council - Arctic Monitoring and Assessment Program	Progress Report on 2nd Phase of Heavy Metals Assessment	2000
	Arctic Council Ministerial Report on 2nd Phase Assessment Results	2002
	Final Arctic Council Ministerial Report on 2nd Phase Assessment Results	2006
Office of Prevention, Pesticides, and Toxic Substances		
CEC North American Regional Action Plan on Mercury	Coordinate Implementation of the Mercury NARAP Phase II over the Next Several Years.	2000 - 2005
Region 5; GLNPO; OPPTS; all EPA Offices		
The Great Lakes Binational Toxics Strategy	Seek 50 percent Reduction Nationally in Deliberate Use of Mercury, and 50 percent Reduction in Releases of Mercury from Sources (air and water) Caused by Human Activity.	2006
	Virtual Elimination of Mercury	Beyond 2006
Region I; all EPA Offices		
The North East Governors-Eastern Canadian Premiers Mercury Action Plan (June 1998)	Virtual Elimination of Anthropogenic Discharge of Mercury	2003

A progress report on heavy metals was presented to the Arctic Council Ministers in Barrow, Alaska in October 2000. It includes preliminary results of the first verification of the Arctic Sunrise phenomenon at Barrow where elemental mercury in the atmosphere suddenly depletes. Over the next year, these and other data will be combined, interpreted, and incorporated into the Heavy Metals Phase II final report due in September 2002. An Arctic Council Action Plan (ACAP) is being developed. This action plan will identify opportunities for international cooperation to eliminate pollution in the Arctic, targeting mercury and persistent organic pollutants. In addition, the PAME working group is drafting a regional action plan to reduce pollution emissions from land-based sources. The action plan includes voluntary commitments by Arctic Council members to reduce emissions of persistent organic pollutants and heavy metals.

The North American Regional Action Plan on Mercury (CEC, 2000): The North American Regional Action Plan (NARAP) for mercury is one of a number of regional undertakings that have stemmed from the North American

Agreement on Environmental Cooperation (NAAEC) between the governments of Canada, Mexico, and the United States. The NAAEC established the Commission for Environmental Cooperation (CEC) to facilitate activities among the three countries. Under CEC Resolution #95-05, the Sound Management of Chemicals (SMOC) Working Group was established. This working group has been involved in developing four NARAPs on PBTs of national and regional concern, one being mercury.

The Mercury NARAP was developed in two phases. Phase I was approved by the CEC Council in October 1997. It set out the strategic framework and approach to be used by the three countries as well as the ultimate goal. The goal is to reduce mercury releases from human activities to levels comparable to naturally occurring levels and fluxes. Phase II, approved June 2000, fully endorses the over-arching objectives and goal of Phase I. It identifies specific mercury use and release reduction actions that the three countries will undertake individually within their countries, and together through a coordinated tri-national effort. An implementation plan will be developed by mid-2001.

The Great Lakes Binational Toxics Strategy (EPA, 1997c): On April 7, 1997, the United States and Canada signed the Great Lakes Binational Toxics Strategy. The strategy establishes a collaborative process to virtually eliminate persistent bioaccumulative, toxic substances resulting from human activity in the Great Lakes basin. For mercury, the strategy sets a U.S. challenge of reducing the use and release of mercury 50 percent nationwide by 2006. The Canadian challenge is to reduce the release of mercury 90 percent in the Great Lakes basin by 2000. The baseline for the U.S. challenges is the most recent year for which there was an inventory available at the time the strategy was signed. For the release challenge, the baseline year is 1990; for the use challenge, the baseline is the U. S. Geological Survey's 1995 mercury consumption estimate.

The Northeastern States and Eastern Canadian Provinces Mercury (NESCAUM, 1998): On June 8, 1998, the New England Governors/Eastern Canadian Premiers (NEG/ECP) signed a resolution concerning mercury and its impacts on the environment and adopted the Mercury Action Plan, which has as its regional goal "the virtual elimination of the discharge of anthropogenic mercury into the environment." The NEG/ECP has established a task force to coordinate and implement the Mercury Action Plan. The plan identifies 45 specific actions to reduce mercury emissions. These actions include: emission reduction targets for specific source categories (e.g., municipal waste combustors, medical waste incinerators, sludge incinerators, utility and non-utility boilers, industrial and area sources), source reduction, and safe waste management of mercury.

ORD has made a concerted effort to engage the Office of International Activities (OIA) and those Regions involved in the above programs in the preparation and review of the *Mercury Research Strategy*. Each will benefit from the scientific information and technical data resulting from the implementation of the strategy.

1. A TMDL is developed for a water body if water quality standards within the body are not being met using technology-based or other effluent controls. It establishes the maximum allowable pollutant loading for a water body (including allocations for point and non-point source loads and a margin of safety) that will result in compliance with established water quality standards (EPA, 1999c).

4.0 RESEARCH AND DATA GATHERING BY OTHERS

4.1 MERCURY AS A CROSS-MEDIA, MULTIDISCIPLINARY PROBLEM

The current interest in mercury and its impacts on human health began with the methylmercury poisonings in Minamata Bay, Japan, in the 1950s (EPA, 1997a). Since then, a wide range of scientific and technical investigations have advanced the worldwide understanding of the human health impacts from acute and chronic exposures to methylmercury. This understanding has been extended over the years to fundamental insights on sources, routes, wildlife effects, and to a lesser degree, risk management of mercury and methylmercury. A thorough treatment of EPA's knowledge on the subject of mercury is presented in the *Mercury Study Report to Congress*, but there are still key scientific questions that need to be addressed. A recent example of addressing this need is the National Academy of Sciences (NAS) report, *Toxicological Effects of Methylmercury* (NRC, 2000). The NAS report analyzes the methylmercury reference dose and recommends a number of research activities on human health effects.

By its very design and focus on the risk management paradigm, ORD is uniquely positioned to lead an integrated research program on assessing and managing risks from mercury and methylmercury. The research proposed in this strategy, however, cannot be accomplished by ORD alone. Other public and private organizations (*e.g.*, federal, state, and local governments, academic institutions, industrial associations) must be involved in addressing the key scientific questions presented in Chapter 5.0. Research on mercury can be most efficient and effective when undertaken in collaboration with other organizations conducting research in areas of common interest and need.

This chapter of the *MRS* identifies organizations involved in scientific and technical investigations, and data and information gathering related to mercury and methylmercury. This is not an exhaustive discussion, but is intended to be indicative of the organizations conducting research and collecting data pertinent to the six key scientific questions and associated research areas presented in the *MRS*. ORD intends to engage many of these organizations (in some cases, collaborations are already underway) and seek their assistance in achieving the goal of the *MRS*. A brief summary of the organizations and their contributions follows.

4.2 FEDERAL ACTIVITIES

Based on the input received from the various members of the research strategy writing team, direct contacts with other organizations, and a review of the literature (both hard copy and on-line), a number of federal organizations can make contributions to the *Mercury Research Strategy*. These organizations and the work they perform are briefly described below.

4.2.1 National Institutes of Health and the National Institute for Environmental Health Sciences

The National Institutes of Health (NIH) and the National Institute for Environmental Health Sciences (NIEHS) have been investigating the adverse human health effects of methylmercury for a number of years. Investigations address the mechanisms of action of methylmercury on the nervous system and evaluate its effects on other systems (*e.g.,* endocrine, immune).

4.2.2 National Center for Health Statistics and the Food and Drug Administration

The National Center for Health Statistics (NCHS) collects biomonitoring data on mercury concentrations in hair and blood of examinees for the National Health and Nutrition Examination Survey (NHANES) IV. This survey provides information on the distribution of mercury exposures in the general United States population, but does not provide information on specific populations that may have higher than typical exposures. The Food and Drug Administration (FDA) monitors mercury levels in fish sold in interstate commerce.

4.2.3 U.S. Geological Survey

The U. S. Geological Survey (USGS) evaluates the mechanisms of methylmercury bioaccumulation in fish and wildlife species. One research program has correlated mercury concentrations in sediment, water, and fish with water and sediment parameters (Krabbenhoft, et al., 1999). Determining the role of sediment microbial communities in the methylation of mercury is another important USGS program. Much of the research is associated with regional assessments, such as those in the Great Lakes or the Florida Everglades. The USGS continues to collect data on mercury in commerce and has been conducting a program to address mercury releases from mining operations in the Western United States. It conducts research in the aquatic and terrestrial transport, transformation, and fate of mercury. ORD has worked closely with the USGS to establish a coordinated research program for the investigation of ecological processes in the field and the collection

of environmental data for model development and validation, particularly in studies related to the restoration of the South Florida Ecosystem.

4.2.4 Department of Defense

In the context of the mercury life cycle, ORD is interested in one of the most challenging issues facing the United States over the long term, elemental mercury retirement. Mercury retirement is currently being considered by the Department of Defense (DOD) for its strategic stockpile of elemental mercury. At a workshop in Baltimore in the Spring of 2000, DOD personnel presented their efforts in addressing the strategic stockpile and invited workshop participants to join them in addressing this issue. They stressed that DOD was not proposing to conduct research on retirement alternatives, but was relying on a call for retirement technologies to be considered as part of an Environmental Impact Assessment that would be prepared.

4.2.5 National Oceanic and Atmospheric Administration

The National Oceanic and Atmospheric Administration's (NOAA) Atmospheric Research Laboratory (ARL), in coordination with EPA and the Department of Energy (DOE), develops numerical simulation models for atmospheric mercury and other air toxics. Thus far, ARL has focused on Lagrangian-type numerical frameworks (*i.e.,* HYSPLIT), rather than three-dimensional fixed grids with high-resolution nesting and complex chemistry like EPA's Models-3/CMAQ. The National Exposure Research Laboratory's (NERL's) Atmospheric Modeling Division is a part of NOAA's ARL that has been assigned to work for ORD. The division reports to the Director of ARL, so there is close coordination between EPA and NOAA's research activities.

4.2.6 Department of Energy

DOE has undertaken an extensive program in pilot and field evaluations of control technologies for mercury emissions from coal-fired utilities. EPA's National Risk Management Research Laboratory (NRMRL) will participate in these evaluations with DOE and the Electric Power Research Institute (EPRI). The emphasis will be on technology performance and cost effectiveness. DOE, in coordination with ORD, is also studying non-thermal disposal alternatives to mercury-bearing mixed wastes (including soils), and alternatives to mercury use in fluorescent light bulbs. DOE's Oak Ridge National Laboratory (ORNL) is conducting studies on the Arctic Sunrise phenomenon and collecting data on landfill emissions and emission measurement techniques.

4.3 STATE AND REGIONAL ACTIVITIES

Many states conduct regular monitoring of mercury levels in game fish that are used in setting fish consumption advisories. In addition, many states conduct fish surveys to assess methylmercury fish tissue concentrations. Examples of state-specific and regional mercury research activities are presented below. Engagement with these regions and states provides a geographic component that informs the *MRS* and allows for the leveraging of information and data that have been collected over the years.

4.3.1 EPA's Region IV and the State of Florida

The State of Florida's South Florida Mercury Science Program is a multidisciplinary team effort (state and federal agencies, universities, industrial groups and associations) to understand and address mercury bioaccumulation in Florida. The major focus of the research is on the Florida Everglades. Research topics include the following: risks to humans and wildlife from mercury, methylmercury concentrations in the food chain, pathways for transformation of mercury to methylmercury, source identification and transport of mercury species in air and water, and actions to reduce mercury levels in fish and wildlife. ORD already has an excellent working relationship with the state officials leading this effort and has been involved in the research aspects of the program for a number of years.

Region IV has teamed with ORD and Florida's Department of Environmental Protection on the Everglades since 1992. The Region manages a team of researchers who provide quantitative, large-scale spatial and temporal biological, water, and soil data on mercury and methylmercury in South Florida. This data provides more multimedia information on mercury and methylmercury than any other geographic location in the United States. Results from this effort are being developed into an empirical model that addresses the interactions of numerous variables affecting mercury bioaccumulation in the Everglades. It will provide the basis for an ecological risk assessment, leading to management recommendations affecting the restoration of the Everglades ecosystem. Numerous new methods have been developed for sampling, analysis, and interpretation as part of this undertaking (Stober, 2000).

4.3.2 The New England States

The New England governors, in concert with the Eastern Canadian premiers, have developed a Mercury Action Plan to support research and analysis that improves regional understanding of mercury sources, impacts, and cycling in the environment (NEG/ECP, 1998). In this plan, two objectives were identified relating to research, analysis,

and strategic monitoring. These objectives are: (1) research and analysis to improve understanding of mercury sources, impacts, and cycling in the environment, and (2) strategic monitoring of mercury emissions, deposition, and fish tissue levels and environmental indicators to measure and track progress.

4.3.3 Other Regional Contributors

Other EPA Regions are developing data and providing information that contribute to the *Mercury Research Strategy*. Region I has encouraged mercury return programs where mercury-containing devices are turned in by citizens and the mercury is recycled. The Region, along with the Northeast States for Coordinated Air Use Management (NESCAUM), is also interested in mercury retirement as mercury supplies exceed demand. The Region co-hosted a workshop on mercury in products, processes, and wastes with ORD during March 1999 in Baltimore, MD. Region V has been a national leader in addressing PBTs, including mercury. The Region has long been a champion of mercury take-back programs and is active in fostering collaborations with the private sector to address mercury removal from products and processes. The Great Lakes National Program Office (GLNPO), under the auspices of the Binational Toxics Strategy, has been working to virtually eliminate mercury in the Great Lakes. GLNPO has also been collecting data in cooperation with Canada on mercury deposition in the Great Lakes area through the Mercury Deposition Network.

Regions VIII and IX are working with ORD and others to address mercury mining issues. They hosted a workshop on assessing and managing mercury from historic and current mining activities, in November 1999 in San Francisco, CA. Region X has been involved in addressing issues related to transboundary transport of persistent, bioaccumulative toxics, including mercury. The Region co-hosted a workshop with the Office of International Activities and others on the subject during August 1999 in Seattle, WA. The Region has expressed an increasing interest in issues related to the "Mercury Sunrise" phenomenon and Alaskan Native and Native American mercury exposures. The Region also co-hosted a workshop with ORD on aquatic and terrestrial transport, transformation, and fate of mercury in May 2000 in Southern Florida.

4.4 PRIVATE SECTOR ACTIVITIES

Scientific activities are under way in some industrial sectors to assess mercury use and releases. ORD is already working with various industries and industrial research and trade organizations to address research and technical issues related to mercury management options. These efforts will inform both industry and the Agency on mercury and methylmercury risk assessment and risk management for the industrial sector.

4.4.1 The Electric Power Research Institute

The Electric Power Research Institute (EPRI) has supported a comprehensive research program on mercury for many years. EPRI works with the electric utility industry to: collect data on fuels (*e.g.,* coal, oil), measure mercury emissions and deposition of those emissions, develop and test models on mercury fate and transport, conduct integrated assessments of exposure and risk, and evaluate control measures to reduce mercury emissions. EPRI has sponsored research covering a broad spectrum of mercury issues related to coal combustion, including the use and effectiveness of mercury sorbents and coal cleaning. It has been supporting the utility industry's data collection effort in response to EPA's Information Collection Request (ICR) on the mercury content of coal and mercury emissions from coal-fired utilities. Since the 1980s, EPRI has sponsored a series of international conferences on mercury as a global pollutant. The last conference was held in Rio de Janeiro, Brazil, in 1999 and the next one will be held in Minamata, Japan, in 2001. Additional information on EPRI's mercury research program can be found at its web site (http://www.epri.com).

4.4.2 The Chlorine Institute

The Chlorine Institute is working with its members in the chlor-alkali industry to reduce mercury use by 50 percent as part of the Binational Toxics Strategy (EPA, 1997c). In the spring of 2000, ORD in cooperation with The Chlorine Institute, EPA Regions IV and V, and OAR conducted a mercury emissions sampling program at a chlor-alkali plant in the Southeastern United States. ORD plans to continue this cooperative relationship to gain an improved understanding of mercury emissions from chlor-alkali plants and to resolve mercury mass balance issues associated with plant operations.

4.5 OTHER DOMESTIC ACTIVITIES

4.5.1 Non-Governmental Organizations

Over the years, non-governmental organizations and citizens groups have played a critical role in addressing mercury and methylmercury issues and focusing the government's attention on the implications of mercury pollution. The regulatory determination on controlling mercury emissions from coal-fired utilities resulted from a Consent Decree issued as part of a settlement agreement between EPA and the National Resources Defense Council (NRDC). Both NRDC, as part of the Environmental Working Group (EWG), and the National Wildlife Federation (NWF) have issued reports on mercury in the environment within the past year (EWG, 1999; NWF, 1999). The Mercury Policy Project is another non-governmental organization involved in advancing both policy and research issues related to mercury. ORD will engage these

and other non-governmental organizations, as it moves to implementation of the *Mercury Research Strategy* in the coming year.

4.5.2 Academic Institutions

Academic research plays a critical role in advancing the fundamental understanding of mercury and methylmercury risk assessment and risk management. ORD recognizes that many of the research needs associated with atmospheric, aquatic, and terrestrial mercury transport, transformation, and fate can best be addressed by researchers in the academic community. To this end, a Request for Applications (RFA) was issued in FY 1999 as part of ORD's Science to Achieve Results (STAR) Grants Program on aquatic and terrestrial transport, transformation, and fate of mercury (EPA, 1998e). Nine grants were awarded at the end of FY 1999 and are summarized in Appendix A. NCER is now considering a second RFA on atmospheric transport, transformation, and fate of mercury to be issued in FY 2001. This RFA will solicit research on many of the issues relate to the chemistry, thermodynamics, and kinetics of atmospheric mercury. Other academic research will also be consulted for its relevance to the *Mercury Research Strategy*. For example, EPA is working with the Energy & Environmental Research Center at the University of North Dakota to address fundamental issues associated with mercury in combustion systems.

4.6 INTERNATIONALACTIVITIES

In the international arena, mercury has been a subject of research for many years. There is ample evidence of the breadth and depth of this international-scale commitment to mercury research based on the *Fifth International Conference on Mercury as a Global Pollutant* held in Rio De Janeiro, Brazil, in 1999 (CETEM, 1999) Technical papers on mercury and methylmercury research were presented by researchers from Brazil, Canada, Finland, India, Japan, Poland, Russia, Slovenia, and the United States, to name just a few of the countries that were represented. These technical papers described a broad spectrum of research related to mercury risk assessment and risk management research (*e.g.,* human and ecological effects and exposure; transport, transformation, and fate; risk management). Government agencies in other countries (*e.g.,* Denmark, Germany, France) are also identifying adverse human health effects of methylmercury and investigating mechanisms of action on the nervous system. Assessments are also being conducted in other countries to describe the dose-response and set the No Observed Adverse Effects Levels (NOAELs) and the Lowest Observed Adverse Effect Levels (LOAELs) for methylmercury.

ORD will work with EPA's Office of International Activities (OIA) and other Program Offices to advance mercury research in the international arena. Cooperative international undertakings are essential in addressing mercury and its impact on the environment. The recent findings of the National Academy of Sciences regarding the EPA's RfD for methylmercury would not have been possible without the many international research projects addressing the human health impacts of methylmercury. Add the United States involvement in a number of international agreements on mercury (*e.g.,* Great Lakes Binational Toxics Strategy, North American Regional Action Plan, Arctic Monitoring and Assessment Program, Convention on Long-Range Transboundary Air Pollution) and it is clear that international mercury research will contribute in many ways to answering mercury risk assessment and risk management questions. Where they have not yet been developed, international strategies will be needed that include appropriate components addressing the research areas presented in the *Mercury Research Strategy*.

4.7 CROSS-ORGANIZATIONAL ENGAGEMENT

ORD is currently collaborating with a number of organizations on mercury research. The most effective vehicle for engaging federal organizations is through the Committee on the Environment and Natural Resources (CENR) under the White House Office of Science and Technology Policy (OSTP). Collaborations with DOE and the USGS are already underway. ORD has engaged USGS on mercury science and research through the USGS/EPA Mercury Roundtable. This engagement is a direct result of comments made by USGS on the draft of the *MRS* through CENR and the realization that a collaboration on mercury research presented a powerful opportunity for both organizations. The first meeting of the Roundtable was held in late-June 2000. USGS has already expanded its representation to other organizations within the Department of the Interior (*e.g.*, National Park Service, Bureau of Land Management, Fish and Wildlife Service).

EPA is working cooperatively with DOE's National Energy Technology Laboratory (NETL), USGS, and the Electric Power Research Institute (EPRI) to develop and evaluate improved mercury measurement methods and more cost-effective mercury emission reduction technologies. A team of individuals from each organization is working together to define and refine roles and responsibilities, identify areas for collaboration, and coordinate the transfer of new information obtained through the research conducted. Understanding the characteristics of different coals and the possibility of cleaning coal before it is burned are important areas in which EPA is relying on other agencies and the private sector. All of these organizations are working with EPA's Office of Air Quality Planning and Standards (OAQPS) and coal-fired utilities to enhance knowledge about the mercury content of various coals. EPRI is conducting studies on coal cleaning as an approach for reducing mercury emissions from coal-fired boilers. DOE

and EPRI will also play a lead role in testing innovative emission control technologies, including multi-pollutant controls, in pilot- and full-scale utility boilers.

ORD plans to engage a number of organizations on risk communication research for mercury, especially targeted at susceptible populations. Risk communication on mercury has been almost exclusively tied to messages about methylmercury in fish. Communicating both the benefits of consuming fish and the accompanying risk of ingesting the contaminants often found in fish is a complex process. The 40 states that have fish advisory programs on mercury also have risk communication programs that typically target susceptible populations. The extent to which these messages are tailored to ethnically-diverse populations varies. Research on factors that complicate communication (*e.g.*, prior beliefs and attitudes, silent questions and concerns) when addressing people of diverse ethnic backgrounds is also a critical component of successfully communicating risk. A great deal of work in this area is either disease-specific (*e.g.*, transmission of HIV), behavior-specific (*e.g.*, smoking cigarettes), or agent-specific (*e.g.*, risks of exposure to lead or radon). Some general work on risk communication appears to have been sponsored by organizations such as the National Science Foundation. State governments, private foundations, and various health agencies (*e.g.*, Centers for Disease Control) conduct research on communicating the risk of various diseases and injuries.

In addition to research targeted at specific aspects of the mercury problem (*e.g.*, human health, management of combustion sources), federal organizations and others are conducting applied research and collecting scientific data and information that informs EPA's efforts on mercury. These efforts are mainly focused on geographic regions or locales where mercury has been identified as a problem. Examples include: (1) the National Estuary Program, administered by EPA's Office of Water – working to restore and enhance 28 nationally significant estuaries; (2) EPA's Great Waters Program – charged to research and resolve environmental issues affecting the Great Waters of the United States (*e.g.*, Great Lakes, Chesapeake Bay); and (3) the National Estuaries Research Reserves System (NERRS), administered by the National Oceanic and Atmospheric Administration (NOAA) – conducting long-term research, education, and stewardship of 23 national estuarine reserves. More thorough descriptions of these examples, and many others are presented in the *Deposition of Air Pollutants to the Great Waters: Third Report to Congress* (EPA, 2000a). ORD will engage these organizations to determine how their programs can make contributions to the Agency's mercury research program.

5.0 RESEARCH AREAS, KEY SCIENTIFIC QUESTIONS AND RESEARCH NEEDS

> ***Mercury Research Strategy Goal***
>
> To provide information and data that reduce scientific uncertainties limiting the Agency's ability to assess and manage mercury and methylmercury risks.

The *Mercury Research Strategy* was designed to identify areas where the Agency's knowledge and understanding of mercury can be improved. In preparing the *MRS*, six key scientific questions were identified that require ORD's attention. The answers to these questions will provide information and data to assist the Agency in assessing and managing mercury and methylmercury risks. This chapter describes the methodology used to identify the research areas and key scientific questions, and to prioritize research needs. It also includes a discussion of how the Agency is implementing research on the needs that were identified. Funding allocations are presented, as are the emphases for the mercury research program over the next five years. The chapter concludes with a detailed presentation of each of the six key scientific questions and associated research needs.

5.1 MERCURY RESEARCH PRIORITIES

5.1.1 Identification of Research Areas

The six research areas described in this *Mercury Research Strategy* were identified through an interactive process between the (ORD) and EPA's Program Offices and Regions. ORD consulted with its EPA customers and asked them to identify those areas in which a lack of scientific and technical knowledge and data related to mercury inhibited their ability to fulfill their missions. Input received from the Program Offices and Regions was categorized into broad research areas organized around the risk paradigm. The research areas identified were: Human Health Effects and Exposure; Ecological Effects and Exposure; Transport, Transformation, and Fate; Risk Management for Combustion Sources; Risk Management for Non-Combustion Sources; and Risk Communication. Writing teams comprised of ORD personnel and representatives from Program Offices and Regions were created to address each research area. The lead writers for each of these writing teams formed the *MRS* Writing Team.

5.1.2 Development of Key Scientific Questions

The key scientific questions identified for each research area were developed by the various writing teams. The questions were formulated, and re-formulated, as the writing process progressed. It was the goal of each of the writing teams to capture the key scientific questions (in some cases the key scientific question includes a series of inter-related sub-questions) in a way that allows for the development of long-term goals as part of the multi-year research implementation plan. These long-term goals are then translated into Annual Performance Goals (APGs) and Annual Performance Measures (APMs) in accord with the Government Performance and Results Act.

5.1.3 Prioritization of Research Areas and Key Scientific Questions

ORD, in consultation with its Program and Regional Office counterparts, established the priorities for the mercury research program. The prioritization process was influenced by an understanding of the regulatory and voluntary drivers facing the Agency (Chapter 3.0). International issues were integrated within each appropriate research area. In addition, the research areas were evaluated by the writing teams to determine the level of funding needed, while maintaining a viable portfolio of research across the six key scientific questions. Priorities are subject to re-evaluation and adjustment depending on a number of factors (*e.g.,* progress in answering the key scientific questions, influential regulatory deadlines, research by other organizations). These factors require that priorities and trends in emphasis be revisited on a year-to-year basis as part of ORD's annual planning process.

5.1.4 Identification of Research Needs

In identifying the research needs for the *Mercury Research Strategy*, the most influential resource was the *Mercury Study Report to Congress* because it contains an extensive analysis of the state-of-the-science understanding of mercury and methylmercury. Each writing team reviewed the research needs described in the *Report to Congress* across the risk paradigm (*i.e.,* human and ecological health effects; human and ecological exposures; transport, transformation and fate; and risk management for combustion and non-combustion sources). The writing teams then matched up research needs with the key scientific questions. ORD and the Office of International Activities (OIA) lead a cross-cutting team addressing international mercury issues.

5.1.5 Prioritization of Research Needs

The research needs under each research area were prioritized using the following criteria:

- Provide timely scientific information and data needed to inform current and future Agency decisions on mercury.
- Fill data and information gaps on mercury not addressed by other organizations.
- Support the goals and objectives of ORD's Strategic Plan (EPA, 1996; EPA, 1997b) which stress research in accord with the risk assessment/risk management paradigm.

ORD's overall research program covers a variety of topics. Some of the investigations underway as part of other research strategies may well contribute to advancing the mercury research program. A preliminary review of the *Ecological Research Strategy*, the *Pollution Prevention Research Strategy*, and the *Waste Research Strategy* (EPA, 1998c; EPA, 1998d; EPA, 1999b) indicates this possibility. Where pertinent scientific information and technical data are being developed under these or other ORD research strategies, resource leveraging will be explored and, when appropriate, employed. Where scientific information and technical data are being developed by other organizations (*e.g.,* USGS, DOE), ORD intends to work collaboratively with these organizations to convey their information and data to appropriate Agency decision-makers. The focus will be on work that complements ORD's efforts and is critical to fully addressing the six research areas.

5.1.6 Peer Panel Review of the *Mercury Research Strategy*

The last step in the prioritization process followed an external peer review of the draft *MRS* conducted on December 9 –11, 1999 in Washington, DC. Ten experts from outside EPA were assembled to review the draft *MRS* and offer their individual and collective opinions on the document. Because the *Mercury Research Strategy* extends across the risk management paradigm, the peer reviewers were selected based on their broad experience, expertise, and the various disciplines that they represented (from risk assessment through risk management). The *MRS* Writing Team was particularly interested in the opinions of the peer reviewers from an interdisciplinary perspective. The writing team wanted to be sure that the scientific issues around mercury and methylmercury were adequately addressed across all research areas. By and large, the peer panel found the priorities to be appropriate, but did recommend an increased emphasis on atmospheric transport, transformation, and fate of mercury. That recommendation and a number of other suggestions were incorporated into this final version of the *MR*S.

5.2 TAKING ACTION ON IDENTIFIED PRIORITIES

In order to achieve the *MRS* goal, ORD is undertaking and sponsoring research that addresses both mercury and methylmercury risk assessment and risk management questions. This research is being conducted by scientists and engineers in ORD laboratories and centers, at universities, by the private sector, and with other federal organizations. ORD plans to take the lead in integrating the results from this research into information that can be used to inform future decisions by the Agency's Program Offices and Regions. Research priorities identified in the *Mercury Research Strategy* will be used to guide decisions relating to ORD funding of in-house research, sponsored research, and collaborative mercury research efforts.

5.3 STRATEGIC DIRECTIONS

Mercury is a human and ecosystem risk and a high priority both within and outside of the Agency. Consequently, internal stakeholders (*e.g.,* Program Offices, Regions) and external stakeholders (*e.g.,* regulated entities, environmental groups, community decision-makers at all levels, the general public, international entities) have an interest in the *Mercury Research Strategy* and its priorities. Stakeholders are particularly interested in research program sequencing and timing in order to determine whether it is consistent with their needs, interests, and Agency target dates. The *MRS* is designed to provide broad strategic directions for ORD's mercury research program in the coming five years. It is not intended to convey detailed information on specific projects. Specifics will be presented in a subsequent ORD mercury research multi-year implementation plan.

ORD's current emphases for the mercury research program from FY 2001 through FY 2005 appear below. This projection was made with an assumed stable funding level of $6.1M per year over that time period. This estimate incorporates funding from ORD's National Center for Environmental Research (NCER) that supports a research program on aquatic and terrestrial transport, transformation, and fate (Appendix A). Of the $6.1M, approximately $2.0M will be targeted toward the Science to Achieve Results (STAR) Grants Program and the remainder will be used to support in-house research activities. Funding projections for the six key scientific questions are presented in Figure 3, but could well change over the course of the coming years. The further into the future the projections go (*e.g.,* FY 2003 - 2005), the more uncertain they become. For each of the research areas, the rationale for the trends follow.

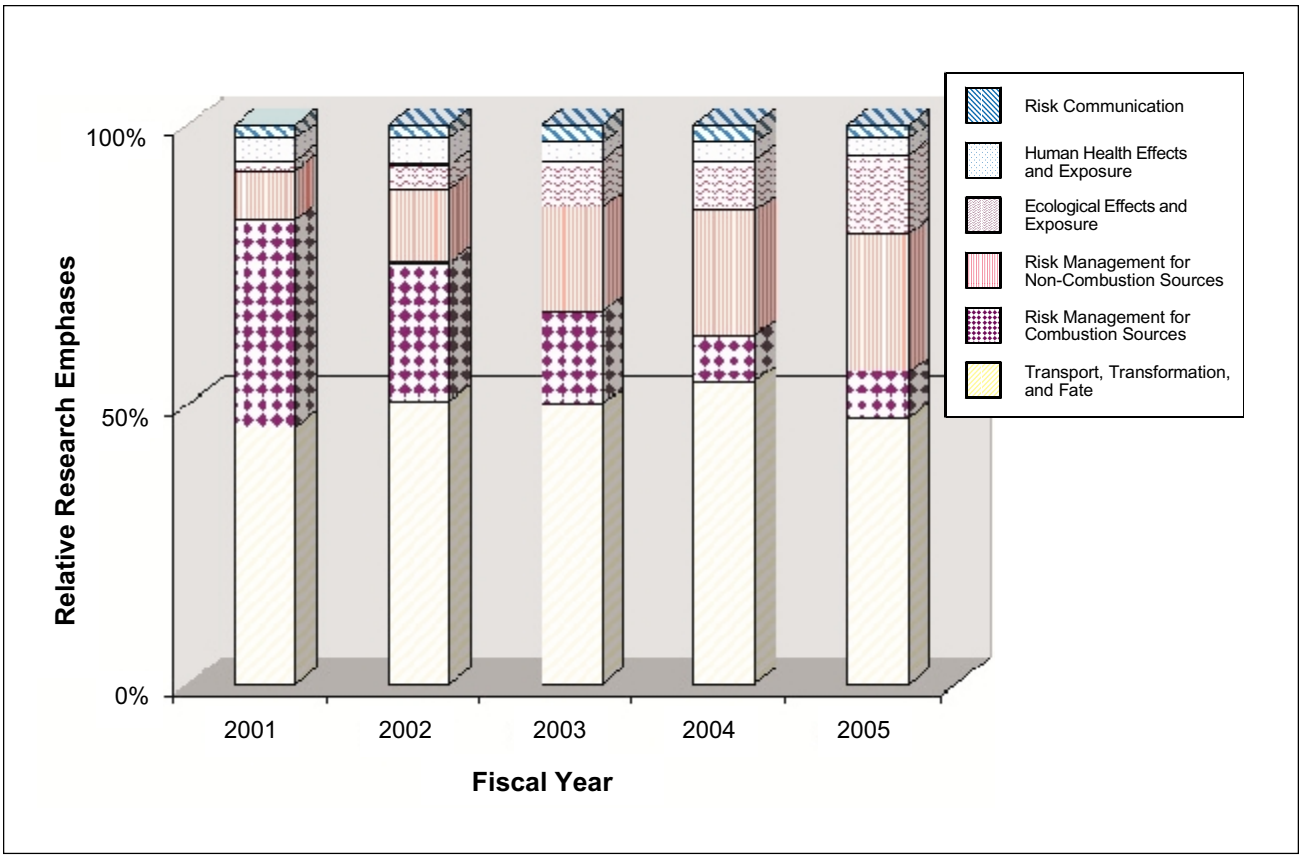

Figure 3. Research Emphases for *Mercury Research Strategy* Key Scientific Questions (FY 2001– FY 2005).

5.3.1 Transport, Transformation, and Fate

Research on mercury transport, transformation, and fate will fluctuate somewhat, but remain relatively stable through the FY 2001-2005 period. Answers regarding this research area will take some time to resolve because transport, transformation, and fate of mercury is so complex once it enters the environment. This research is considered a high priority and will allow an improved understanding of mercury in the environment in terms of any future regulatory efforts. Ultimately, such understanding will lead to more cost-effective risk management approaches for mercury and methylmercury. Expertise in ORD is available in the National Exposure Research Laboratory (NERL), but will be supplemented by a series of projects under the STAR Grants Program. (Refer to Appendix A for additional information.)

5.3.2 Risk Management for Combustion Sources

Research to manage risks from combustion sources addresses the highest near-term mercury priority and will require a significant proportion of the *MRS* budget from FY 2001 through FY 2003, with a gradual decrease thereafter. Combustion risk management research is needed to provide the Agency with the latest information on control technology performance and cost. This will support the development of an official regulatory proposal for coal-fired utilities by FY 2004. EPA's National Risk Management Research Laboratory (NRMRL) has the facilities and expertise to conduct this research and is working with other federal agencies, including DOE, USGS, and EPRI, to demonstrate the most promising technologies for managing mercury from combustion sources.

5.3.3 Risk Management for Non-Combustion Sources

Research to manage risks from non-combustion sources will be modest in FY 2001 and FY 2002, but then increase over the FY 2003-2005 time frame as the need for risk management research for coal-fired utilities decreases and other mercury sources become more prominent. The research will provide information to support future assessments, rulemaking, and voluntary actions with an

early emphasis on source characterization. Expertise in source characterization and control technology for non-utility sources of mercury and methylmercury is available in NRMRL. Other federal agencies (*e.g.,* USGS, DOE) and private organizations (*e.g.,* the Chlorine Institute) must also be engaged.

5.3.4 Ecological Effects and Exposure

Research on the effects of methylmercury have been demonstrated in ecological systems (EPA, 1997a), but there is a need to learn more about its effects, particularly with respect to fish-eating wildlife. Ecological research will assist the Office of Water (OW) in the development of aquatic and wildlife water quality criteria and will gradually increase over the FY 2001-2005 period. This research will be split evenly between effects and assessment activities. Expertise is available within ORD for both types of research (National Center for Environmental Assessment - [NCEA] and National Health and Environmental Effects Research Laboratory - [NHEERL]), but research being conducted by other federal agencies such as the USGS and projects under the STAR Grants Program also contribute to ORD's efforts in this research area.

5.3.5 Human Health Effects and Exposure

The National Academy of Sciences (NAS) report on the health effects of methylmercury supported EPA's reference dose (RfD) of 0.1 micrograms per kilogram body weight per day as a scientifically justified level to protect human health. There are, however, several research areas identified in the NAS study that need to be addressed. Also, there is a continuing need for ORD to support OW in the development of a revised human health water quality criterion for mercury in FY 2001, and to assist OAR in promulgating regulations to control mercury from coal-fired utilities in FY 2005. Level support in this research area is projected through the FY 2002 - FY 2005 time frame. NCEA is capable of providing technical support and conducting risk assessments, and is leading this effort.

5.3.6 Risk Communication

Research to improve communication to populations at risk of elevated exposures to methylmercury from fish will fluctuate slightly over the FY 2001-2005 period. The Agency needs to develop communication approaches to address risks specific to those who consume large quantities of fish (*e.g.,* persons of Native American and Asian ethnicity) and those who are at heightened risk because of nervous system vulnerability (*e.g.,* maternal-fetal pair, nursing mother-infant pair, and young children). NCEA will be responsible for this effort and will use both contracts and cooperative agreements in its undertaking. NRMRL is also available to provide research and support on technical information transfer vehicles and venues as part of ORD's efforts in stakeholder engagement.

5.3.7 Strategic Directions Summary

The six key scientific questions in the *MRS* will meet domestic regulatory commitments and offer international opportunities for addressing mercury. Pressing policy and legislative issues drive ORD's human health and environmental research priorities. While the *Mercury Research Strategy* remains grounded in the risk management paradigm, addressing Program Office and Regional research needs over the next several years is central to its success; ORD plans to focus on those research needs in the near term by stressing the transport, transformation, and fate and combustion risk management research areas. In the longer term, research that advances the understanding of human health effects and exposure, ecological effects and exposure, and non-combustion risk management will be emphasized. Research on communicating the risks of methylmercury exposure to those individuals and groups at greatest risk will be an ongoing effort.

5.4 DETAILED DISCUSSION OF RESEARCH AREAS, KEY SCIENTIFIC QUESTIONS, AND RESEARCH NEEDS

This section of Chapter 5.0 provides a detailed description of the research to be undertaken for each of the six key scientific questions and associated research areas. Each description includes a discussion on background, program relevance, prioritized research needs, research results, and measures of success. The description also contains a list of preliminary performance goals that will be used in mapping out the multi-year implementation plan for the mercury research program. The research needs are identified in order of their relative priority. Each is accompanied by a narrative, the intent of which is to describe the type of work that would be required to address the need.

5.5 TRANSPORT, TRANSFORMATION AND FATE

5.5.1 Key Scientific Question

How much methylmercury in fish consumed by the U.S. population is contributed by U.S. emissions relative to other sources of mercury (such as natural sources, emissions from sources in other countries, and re-emissions from the global pool); how much and over what time period, will levels of methylmercury in fish in the U.S. decrease due to reductions in environmental releases from U.S. sources?

5.5.1.1 Background

Mercury bioaccumulates most efficiently in the aquatic food web. Fish-eating birds and mammals at the top of the food web generally have higher methylmercury concentrations. Nearly all of the mercury that accumulates in fish tissue is methylmercury. Inorganic mercury, which is less efficiently absorbed and more readily eliminated from the body than methylmercury, does not tend to bioaccumulate. The *Mercury Study Report to Congress* supports a plausible link between releases of mercury from industrial and combustion sources in the U.S. and methylmercury in fish. However, fish methylmercury concentrations may also result from existing background concentrations (mercury from natural sources, as well as re-emitted mercury deposited from previous human activity) and deposition from the global reservoir (which includes mercury emitted by other countries).

Given the current scientific understanding of the environmental fate and transport of this element, it is not possible to quantify how much, and over what time period, levels of methylmercury in U.S. fish will be reduced by reductions in environmental releases from United States sources. Also, it is unclear how much of the methylmercury in fish consumed by the U.S. population is contributed by emissions from other United States sources (such as natural sources and re-emissions from the global pool). As a result, decision makers do not have quantitative information to relate potential reductions in environmental releases to reductions in exposure.

5.5.1.2 Program Relevance

As methylmercury is the primary route of exposure to both humans and wildlife, it is critical to understand the relationship among methylmercury in fish, levels of ambient mercury in the environment, and emissions from all sources. It is accepted that fish consumption dominates the pathway for human and wildlife exposure to methylmercury. Therefore, a better understanding of this pathway and, to the extent possible, the quantitative relationships among fish intake, methylmercury burdens, residuals in the environment, deposition and emissions, will reduce uncertainties in both risk assessment and risk management. Information on this issue will assist the Agency in prioritizing the management of the diverse sources of mercury in the environment including regulation of combustion sources, pollution prevention activities, remediation of residuals, and international activities. The research being conducted under the Office of Research and Development's (ORD) Science to Achieve Results Program (STAR) will support the first and third prioritized research needs described below.

5.5.1.3 Prioritized Research Needs

- *Improved understanding of the transport, transformation, and fate of mercury in the atmosphere.*
- *Enhanced monitoring of atmospheric mercury deposition for model application.*
- *Improved understanding of the transport, transformation, and fate of mercury in the aquatic and terrestrial media.*
- *Enhanced monitoring of mercury and methylmercury in the aquatic and terrestrial media for improved risk management.*

Research and monitoring needs have been identified in four categories that follow the predominant pathways of exposure from emissions to fish uptake: atmospheric transport, transformation, and fate processes; deposition of mercury from the atmosphere to terrestrial and aquatic environments; fate, transport, and transformation processes in aquatic and terrestrial environments; and monitoring of spatial and temporal patterns of mercury and methylmercury in fish and sensitive environments. The key scientific question encompasses a number of subsidiary questions, including: factors influencing global, regional, and local mercury cycles; factors controlling local deposition and methylation of mercury; and effective monitoring programs.

Improved understanding of the transport, transformation, and fate of mercury in the atmosphere. A need exists to provide quantitative estimates of air concentrations and deposition of elemental mercury, reactive gas-phase mercury, and particulate mercury in the U.S. to improve the Agency's understanding of the fate, transport and transformation of mercury. Improvements in atmospheric models will be important in the next few years. Obtaining information on the chemical species and physical form of mercury in emissions, in the atmosphere, and in deposition is vital to accurately modeling the transport and fate of mercury. There is a clear need for atmospheric models (range of 50 to 200 kilometers) to be used in the development of emissions limits to protect water quality, human health, and ecological health.

- *Information from an atmospheric modeling framework.* This framework will be based on ORD's new multi-pollutant air modeling system (Models-3), which is being developed and tested for ozone and particulate matter by National Exposure Research Laboratory (NERL) researchers. This new system will replace the highly-parameterized modeling approaches for mercury now in use. The largest process uncertainties are in-cloud chemistry, in-air chemistry and dry deposition of oxidized mercury gas, and these issues will be the focus of a future STAR Request for Applications. As part of this effort, available meteorological, land use, and emissions data will be collected, formatted, and included in the modeling framework. Model runs will be per-

formed using seasonal aggregation approaches to produce an annual mercury depiction that includes source attribution, providing better estimates of the distribution of atmospheric deposition.

- *Field measurements of speciated elemental and oxidized mercury concentrations in air throughout a region at varying altitudes, to characterize gaseous and aqueous processes.* These data will be used to validate models of atmospheric chemistry affecting mercury deposition and will also facilitate process understanding. NERL's researchers are currently collecting information in South Florida as part of existing interagency projects involving federal, state, and local agencies. The study includes improved inventories of emission sources in the South/Central Florida region, characterization of the vertical atmospheric profile in the region, including the identification of trace elements and their relative concentrations, and atmospheric modeling of the southern and central Florida atmosphere. Results will be used to determine if global, continental or natural forces govern mercury deposition in the region. A protocol will be developed suitable for other regions of the country. This type of study has been identified as a critical need in addressing source attribution issues in South Florida, particularly in distinguishing between local and global sources.
- *Short-range atmospheric transport models (50 - 200 kilometers) to predict air concentrations and deposition.* This modeling range is needed for many analyses, such as Total Maximum Daily Load (TMDL) calculations used to link specific sources on a local scale to deposition in specific watersheds and water bodies that may be 10- to 100-200 km distant. There are no existing models that are well adapted to this scale. Current urban-scale models generally address only 50 km, which is too small, while national/regional-scale models (covering nearly half the U.S.) do not have sufficiently fine resolution. NERL researchers will examine adding this scale to its current models.

To provide quantitative estimates of air concentrations and deposition of elemental mercury, reactive gas-phase mercury, and particulate mercury in the U.S. that are associated with sources outside the U.S., the following scientific information is needed:

- *Information on the atmospheric fate of mercury species in various scenarios.* Little is understood about the atmospheric chemistry and fate of mercury in the Arctic, and especially of a recently observed mercury depletion event occurring during the Arctic Sunrise, when photolytic reactions significantly affect the behavior of atmospheric mercury and its deposition during the Spring months. The Agency needs to understand the mechanisms for atmospheric mercury depletion, whether the mercury is becoming particle-bound and/or transforming to reactive gaseous mercury which affects deposition rates and subsequent bioaccumulation, and whether similar processes occur for ozone depletion. The answer to these questions are critical because partitioning to particulate-and reactive gas-phase could increase the possibility for bio-uptake through the food chain once deposited. This event occurs just prior to the time when Arctic ecosystems are most active. Preliminary research on this topic is being conducted by NERL researchers and researchers from other organizations (e.g., DOE) and is sponsored by OIA.
- *Information on transport mechanisms affecting cross-boundary pollution.* Recent scientific evidence points to a rapid (3-5 day) trans-Pacific transport mechanism tied to meteorological conditions that could bring persistent bioaccumulative toxics (PBT) contaminants, including mercury, to the west coast of North America, Alaska, and the Arctic. The data show higher levels being transported in late Winter-Spring, concurrent with the timing for Arctic Sunrise. The probabilistic nature of the jet stream controlling trans-Pacific toxic compound (mercury) transport needs to be understood if the Arctic Spring event is to be fully appreciated. This is a topic being pursued by OIA as part of an *International Mercury Strategy*.
- *Field-test results of a mercury measurement technology that has been developed to determine both urban and background concentrations of gas-phase elemental mercury and particulate mercury.* These measurements, coupled with trace element and back trajectory analyses, permit the modeling of mercury transport to the U.S. from sources abroad. Through international cooperation, similar methods can be used abroad to enhance the U.S. emissions mass-balance analysis. These instruments would be used to evaluate the effectiveness over time of the United States and international mercury emission controls. Early international harmonization of instrumentation and mercury sampling protocols is also needed to compare data and identify which data are most appropriate for use in trends assessment and modeling. Again, this is a topic being pursued by OIA as part of an *International Mercury Strategy*.

EPA must also begin the development of a global scale model for mercury transport, transformation, and fate, including improved emission inventories. Risk management actions to reduce global levels of background mercury are dependent on an understanding of the mechanisms driving mercury flux, which aids in the identification of effective mediation. Without a better understanding of mercury flux from existing mercury pools in the oceans, wetlands, aquatic sediments, Arctic tundra and ice sheets (and wherever else it is sequestered), the context for estimating the current or near-term mercury emissions from anthropogenic sources will be ill-defined. There is a need to establish time lines for natural emission processes.

Research in the Arctic is very important because of unique, natural meteorological conditions there which enhance atmospheric transport of contaminants to the Arctic and then trap them there due to cold conditions. Unique atmospheric transformation processes for mercury are just beginning to be investigated in the Arctic. Researchers are learning that transformation from elemental to reactive gaseous mercury (RGM) is enhanced with increased deposition in Spring. Because mercury and other toxics are trapped there, they tend to be highly bioconcentrated in organisms which have short food chains to top predators, including humans. The most vulnerable populations to mercury exposure are those reliant on indigenous foods tied to fish consumption, and Alaska has native tribes and villages which depend heavily on subsistence foods, including polar bear and marine mammals, and fish-eating birds and their eggs. Research is needed in the Arctic, to understand unique processes, and ecological and human health linkages.

An additional concern is the effect of global warming in the Arctic, and potentially enhanced release and methylation rates for mercury over the next 20-100 years because of warming trends. There is a need to understand the relative importance of aquatic transport of mercury across international boundaries. Tracers can be used to identify current and historic mercury emitter source types. Significant quantities of mercury may be transported in dissolved or particulate form within aquatic systems to food chain receptors, either from direct discharge, including erosion of soils or sediments within a watershed, or through air deposition to water bodies. Mercury may also cross international boundaries via shared waters. Because the *Mercury Research Strategy* is focused primarily on resolving domestic issues related to mercury and methylmercury risk assessment and risk management, these topics must be addressed in the larger context of the international implications of mercury.

Enhanced monitoring of atmospheric mercury deposition for model application. There is a need to improve the monitoring of atmospheric mercury deposition. NERL will begin development of a coordinated mercury monitoring program, in cooperation with the USGS and other federal and state agencies, through installation of comprehensive deposition monitoring stations in highly impacted, highly sensitive geographic regions such as South Florida, the Northeast, the upper Midwest, and the Arctic. Of particular importance is obtaining data on the spatial and temporal distribution of mercury deposition to determine source-receptor relationships and to measure patterns of long-range deposition. The objective is to quantify the contributions of mercury to terrestrial and aquatic systems from local, regional, and global sources. To address this question, ORD has proposed the development of specialized platforms for atmospheric mercury deposition monitoring and source attribution. The platforms will be capable of comprehensive, speciated measurements of mercury and related species, and will provide deposition data to compare with source-signature information. Platforms can provide valuable information on mercury deposition resulting from international sources, and will contribute to agreements such as the United States-Canada Binational Agreement and the North American Regional Action Plan for Mercury developed by the North American Commission on Environmental Cooperation. The platforms will have the capability to report on hourly-to-daily, dry and wet deposition of speciated mercury needed for transport and fate models, source identification, controls planning and, ultimately, direct measurement of mercury control benefits.

Improved understanding of the transport, transformation, and fate of mercury in the aquatic and terrestrial media. There is a need to develop a better understanding of the processes (especially microbial and plant-mediated processes) that mediate ecological exposures to methylmercury. A key need is understanding the environmental cycling of mercury, especially the characteristics that induce methylation of mercury in ecosystems, and the pathways of mercury and methylmercury exposures to fish and marine mammals. In particular, the role of sulfur and selenium in controlling the toxicity and/or bioavailability of methylmercury is poorly understood. Terrestrial and aquatic models incorporating current process understanding at different scales will be developed and validated. These models must be fully consistent and integrated with the atmospheric models discussed above. Fundamental research is being conducted as part of the NCER's STAR Grants Program (Refer to Appendix A).

In cooperation with other federal, state, and local agencies and industrial groups, ORD will also complete field and model studies in South Florida, and then test and apply the techniques developed to the Northeast and Midwest along the Canadian border, to western mining issues, and to coastal and high-elevation ecosystems. The long-term goal is to develop a spatially structured model for describing and predicting the processes controlling mercury and methylmercury exposures for fish and wildlife under current and restoration conditions. The objective of the project is the construction of biogeochemical and community bioaccumulation models that interface with the hydrology and water quality models that are the basis for evaluating restoration goals. Such a linked, spatially distributed model will be critical for assessing multiple interactive stressors, for analyzing the spatial component of mercury and methylmercury exposures (*e.g.,* methylmercury concentrations in local fish populations vs. nesting/foraging areas for wading birds), and for evaluating the effectiveness of criterion-based restoration goals. The work in South Florida presents a unique opportunity to leverage ongoing studies with other federal agencies (*e.g.,* Fish and Wildlife Service, National Park Service, EPA Region IV), the Florida Department of Environmental Protection, the Florida Game and Fish Commission, the South Florida Water Management District, and the Electric

Power Research Institute. Lessons learned in this ongoing project will be applied nationwide.

Critical questions for wildlife exposure and biological transport to humans include: (1) to what extent does transboundary transport of mercury occur via migratory species when boundaries are shared between the U.S. and other countries (including shared water bodies), (2) and how significant is this fish and wildlife migration for vulnerable U.S. wildlife and human populations due to uptake through the food chain? EPA knows that older fish of some species have elevated levels of mercury, and this is also true of beluga whales and sea otters. Likewise, there are concerns for mercury levels in birds such as eider (an endangered species) and loons. Information about migratory patterns and behavior of migratory fish, marine mammals, migratory birds and other species of importance in the food chain is needed and will be addressed as part of the *International Mercury Strategy*.

EPA believes that this is an important research area, in that more information is becoming available showing that migratory species with body burdens of toxics (which could be enhanced by their spending time in more highly polluted areas in other countries, such as Russian waters, or areas near industrial Asian sources) can release the bioaccumulated contaminant to the environment to which they migrate, and enhance bio-uptake there. It is known that the large predatory fish, tuna, is one of the most wide-ranging animals, can cross the Atlantic in fewer than 50 days, and lives to be 40 years old. Migratory salmon and whales can spend time in Russian waters and then migrate back to Alaska, and migratory birds do the same. These are all eaten directly by indigenous peoples in Alaska , and bird eggs are also consumed. They constitute a large part of the indigenous diet. Recent studies of PCBs in bird eggs in Alaska showed elevated levels. Fish in the Bering Sea are a tremendous resource for consumers there and also in the lower 48 States. It is important to know if Arctic species are being more contaminated via direct migration to areas where uptake can be enhanced, or indirectly through food linkages to such more highly-exposed animals. It is premature to say that transboundary linkages are insignificant from a food chain perspective.

Enhanced monitoring of mercury and methylmercury in the aquatic and terrestrial media for improved risk management. The Clean Water Action Plan (EPA, 1998a) calls for a survey of a wide range of pollutants in fish tissue (including mercury). There are two basic goals: (1) provide a statistically representative distribution of those chemicals known to accumulate in fish flesh and (2) determine whether there are other chemicals of concern. Designed by ORD's Environmental Monitoring Assessment Program (EMAP) Program and administered by OW, this survey is statistically based so that it is repeatable and able to detect trends in mercury and to measure progress toward attaining Government Performance and Results Act (GPRA) goals. This technique has proven effective in a survey of northeastern lakes (Yeardley, et al., 1998). To complement the national survey, there is a need to develop a longer-term monitoring program which links existing and planned deposition monitoring sites with sentinel environments where mercury methylation is most likely to occur (*e.g.,* wetlands).

5.5.1.4 Research Results

Results from this research will provide an improved understanding of the fate and transport of mercury and methylmercury in all environmental media and will allow the Agency to identify those mechanisms that are most active in mercury transformation processes. Linked to an improved understanding of mercury releases from sources and sinks, this research will also allow the Agency to better estimate U.S. contributions to mercury in air and water, and on land. Research on transport, transformation and fate will also indicate how reductions in mercury through both regulatory and voluntary actions result in concomitant reductions in methylmercury in both humans and wildlife. This work will be particularly useful for risk managers when considering technological approaches to managing methylmercury in aquatic and terrestrial settings.

5.5.1.5 Measures of Success

Researchers hope to advance the following:

- Measurable improvement in the scientific understanding of the linkage among methylmercury in fish, ambient mercury in the environment, and emissions.
- Identification and control of other pollutants that exacerbate or minimize the mercury problem (*e.g.,* acid, sulfur, selenium, nutrients).
- Completion of a national sampling plan for methylmercury and other persistent chemicals in fish tissue.
- Successful demonstration of a monitoring platform capable of measuring the spatial and temporal distribution of mercury deposition to determine source-receptor relationships, and to measure patterns of long-range deposition.
- Completion of a multimedia integrated modeling system capable of quantifying regional exposure to mercury; of evaluating the relative importance of local, regional, and global sources of mercury; and of determining the importance of natural sources, re-emitted mercury formerly deposited from anthropogenic and geological sources, and new emissions.

5.5.1.6 Preliminary Performance Goals

- By 2003, develop a continuous ambient monitor capable of distinguishing atmospheric mercury species.

- By 2006, provide an improved model for mercury in terrestrial and aquatic systems capable of tracking the fate of mercury from sources to concentrations in fish tissue.
- By 2008, produce an improved atmospheric fate and transport model for mercury capable of distinguishing among sources of mercury deposition; along with an assessment of atmospheric mercury transport and fate, including an enhanced scientific understanding of, and then an improved inventory for, the chemical and physical forms of mercury emissions.

5.6 RISK MANAGEMENT FOR COMBUSTION SOURCES

5.6.1 Key Scientific Question

How much can mercury emissions from coal-fired utility boilers and other combustion systems be reduced with innovative mercury and multi-pollutant control technologies; what is the relative performance and cost of these new approaches compared to currently available technologies?

5.6.1.1 Background

Combustion systems that burn fossil fuels such as coal or waste materials containing mercury are major sources of mercury emissions to the air. Mercury emissions from these anthropogenic sources eventually get deposited in water bodies or on land. The amount of mercury deposited in the United States that can be directly attributed to domestic combustion sources remains uncertain. However, a report released in 1998 by the Northeast States for Coordinated Air Use Management (NESCAUM) contains results from regional modeling studies supported by EPA (Regional Lagrangian Model of Air Pollution [RELMAP]) that indicate 77 percent of mercury emissions (anthropogenic and natural) deposited in the Northeast are from sources within the United States; and only 23 percent come from the global pool (NESCAUM, 1998). In order to reduce the risks of mercury over time, cost-effective strategies are needed both domestically and internationally to minimize or eliminate mercury emissions from combustion facilities and other anthropogenic sources. While increased use of natural gas for power generation and implementation of recent Clean Air Act (CAA) regulations for several types of waste combustion systems will result in some reductions of combustion-generated mercury, combustion facilities remain a significant source in the United States (accounting for 87 percent of the total point source emissions) with coal-fired utility boilers being the largest single source type (EPA, 1997a).

5.6.1.2 Program Relevance

A substantial reduction of mercury emitted from waste combustion systems is expected to occur over the next several years as final emission standards promulgated by the Office of Air and Radiation (OAR) for municipal waste combustion systems (MWCs) and medical waste incinerators (MWIs) are implemented, and standards proposed by the Office of Solid Waste (OSW) for hazardous waste incinerators (HWIs) are finalized. However, standards for electric utilities and other commercial and industrial boilers have not yet been proposed. Current concerns about the lack of adequately demonstrated, cost-effective mercury emission control technologies applicable to coal-fired boilers and associated equipment pose constraints to development of mercury emission reduction requirements for these sources. As a result, OAR has identified research needs on emission reduction options for utility boilers as its highest mercury research priority. To address OAR's needs, mercury combustion control research will focus on determining the cost and effectiveness of viable options to reduce mercury releases from coal-fired boilers. While the emphasis will be on coal-fired boilers, fundamental research on mercury behavior in combustion systems will be applicable to other boiler types, including those waste-burning industrial boilers and furnaces that OSW has identified as priorities for research. The research results will also be useful to international organizations and countries concerned with mercury emissions from combustion sources. ORD will work with the Office of International Activities (OIA) to develop appropriate technology transfer documents that summarize research findings and to provide technical support for any international demonstrations.

Reducing mercury emissions from combustion sources is complex because there are a wide variety of fuels and waste streams and many different types of combustion configurations, flue gas cleaning methods, and operating modes. Conventional options such as fuel switching, fuel pretreatment (i.e. coal cleaning), waste feed limitations and activated carbon injection are available to reduce emissions; however, there are many instances where these approaches do not achieve adequate emission reductions, are not practical, or have been inconsistent or ineffective in the field. The effectiveness of different control methods is influenced by variables such as the properties of the fuel or waste, the source operating conditions, flue gas cleaning technologies employed, and the species of mercury in the flue gas. In combustion systems, mercury is volatilized and converted to elemental mercury vapor (Hg^0) in the high-temperature regions of furnaces. As the flue gas is cooled, mercury is converted to gas-phase ionic (Hg^{+2}) and particulate-bound (Hg_p) forms of mercury.

"Speciation" is a term used to denote the relative amounts of Hg^0, Hg^{+2}, and Hg_p in flue gas. The rate of conversion of gaseous Hg^0 to Hg^{+2} and Hg_p is dependent on the temperature, flue gas composition, and the amount and properties of entrained particles (fly ash and sorbents). Mercury speciation is a particularly important variable for flue gas cleaning because it directly impacts the capture of the mercury. For example, mercuric chloride ($HgCl_2$) is water soluble and readily reacts with alkali metal oxides in an acid-base reaction; therefore, conventional acid gas scrubbers used for SO_2 control are effective in controlling $HgCl_2$. However, elemental mercury Hg^0 is insoluble in water and must be adsorbed onto a sorbent or converted to a soluble form that can be collected in a wet scrubber. In incinerators, the flue-gas concentration of chlorine is substantially higher than that of Hg^0, and results in preferential conversion of Hg^0 to $HgCl_2$. In coal-fired combustion units, where concentrations of chlorine are much lower and SO_2 is present, mercury may remain predominantly in the elemental form.

In the United States, the control of mercury in MWCs and MWIs is based on the injection of powdered activated carbon upstream of an electrostatic precipitator or fabric filter. Current data from EPA's Information Collection Request (ICR) for coal-fired utility boilers and recent field tests indicate that significant mercury capture is being achieved at coal-fired electric utility boilers through inherent fly ash sorption and collection in existing particulate matter (PM) collectors. These data also indicate that even more substantial capture occurs for systems using sulfur dioxide ($SO_{2)}$ scrubbers and post-combustion nitrogen oxide ($NO_{x)}$ controls. Significant additional control of mercury emissions will require either addition of dry sorbents upstream of the existing PM controls or will be achieved through implementation of advanced controls and strategies for compliance with fine PM, ozone non-attainment, regional haze and New Source Review requirements, as well as efforts undertaken to reduce Toxic Release Inventory (TRI) pollutants such as hydrochloric acid (HCl) and sulfur trioxide (SO_3). Future development of optimal mercury and multi-pollutant combustion source controls will therefore require an improved understanding of the fundamental processes that influence the species of mercury emitted, and testing and evaluation of innovative approaches to capture mercury in an environmentally and economically acceptable manner. In this regard, several of the *critical uncertainties* are:

1. how mercury speciation and capture in combustion systems is influenced by fuel or waste properties, combustion conditions, and flue gas cleaning methods;
2. the extent to which modifications in combustion and flue gas cleaning conditions can cost-effectively reduce emissions of various mercury species and co-pollutants;
3. how to measure combustion source emissions of mercury on a continuous basis; and
4. whether mercury contaminated residuals from air pollution control systems will need to be stabilized before disposal.

Over the next three to five years, ORD will work with the Department of Energy (DOE), the United States Geological Survey (USGS), and private sector organizations to address the key scientific uncertainties described above. Studies will be conducted to identify, evaluate, and demonstrate innovative technological solutions that can cost-effectively reduce mercury emissions from currently unregulated sources or those for which improved technologies would significantly reduce the costs to comply with existing regulations. The relative costs of controlling mercury only and of controlling mercury in conjunction with other pollutants such as fine (PM) and fine PM precursors (sulfur dioxide and nitrogen oxides) will also be quantified.

The four research areas identified below were chosen based on priorities identified by OAR, OSW, and external stakeholders; scientific uncertainties (data gaps) that currently impede implementation of mercury controls for specific sources; and the potential to reduce control costs. Research in these areas is critical to support future regulatory impact analyses, particularly those that include mercury in a multi-pollutant framework, and to ensure that viable options are available for all types of boiler configurations and associated operating conditions. In addition, without adequate data on *combustion chemistry and associated operating conditions,* it will be difficult to develop better technologies and to understand why existing technologies do not perform consistently in the field.

5.6.1.3 Prioritized Research Needs

- *Improved understanding of managing mercury species in combustion processes.*
- *Improved understanding of performance and cost of mercury emissions controls.*
- *Increased testing and evaluation of mercury continuous emission monitors.*
- *Improved characterization of, and management approaches for, mercury controls residuals.*

Improved understanding of managing mercury species in combustion processes. A need exists to determine the parameters, including chemical and physical mechanisms and combustion operating conditions, that affect mercury species emitted from combustion systems, and to identify potential approaches to capture these species. The capture of mercury in a pollution control device is dependent on mercury speciation *(i.e.,* the chemical forms of mercury). A fundamental understanding of the chemical and physical mechanisms and combustion conditions that influence the speciation of mercury in a combustion system is essential to determine the approaches that will provide

effective capture. Specific research planned will: (1) determine how fuel or waste properties, combustion conditions (temperatures, residence times, and quench rates), flue gas composition, fly ash, and sorbent properties, and flue gas cleaning equipment affect mercury speciation; (2) evaluate whether mercury speciation can be controlled by using reagents, catalysts, or adjustments to the combustion process conditions; (3) identify fly ash, sorbent, and flue gas properties that lead to high levels of mercury adsorption and determine whether changing combustion conditions will enhance adsorption; (4) determine the solubility of different mercury species as a function of different scrubber operating conditions (temperature, dissolved species, and reagents); and (5) determine the scrubber conditions necessary to convert Hg^0 to the easier-to-capture species. NRMRL will conduct bench- and small pilot-scale research on mercury behavior and innovative capture methods, and the most promising innovations will be evaluated on larger pilot-scale facilities.

Improved understanding of performance and cost of mercury emissions controls. A need exists to develop information on performance and cost of specialized sorbents, reagents, and control equipment that can be used to reduce mercury emissions from utility boilers and other combustion sources. Conventional flue gas cleaning technologies are not always appropriate for controlling mercury emissions, and special sorbents, reagents or equipment must be used for more effective control. The performance of technologies for controlling mercury emissions is dependent on a number of factors that include the effectiveness of sorbents and reagents and the physical/chemical conditions that determine mercury capture (temperatures, resident times, flue-gas composition, fly-ash properties, sorbent concentrations, reagent concentrations, and the diffusion or mixing of reactants). Based on the research conducted to characterize mercury speciation and control mechanisms and develop sorbents, field tests will be conducted to evaluate the effectiveness of different equipment configurations, reagents, sorbents, and process conditions for controlling mercury emissions. Studies to determine the potential mercury emissions reductions that can be achieved by technologies currently used to reduce criteria air pollutants will also be conducted. Preliminary evaluation of ICR data indicates that technologies currently in place for control of criteria pollutants achieve reductions in mercury emissions that range from less than 10 percent to more than 90 percent. The level of co-control currently achieved can be increased by application of mercury retrofit technologies. Improved mercury control can also be achieved by methods designed to increase capture of more than one pollutant. This approach can utilize the synergisms that accrue through the application of multi-pollutant control technologies. The co-benefits can be maximized by linking mercury control to the reduction of the other regulated pollutants such as NO_x, and SO_2.

Current estimates of mercury control costs using powdered activated carbon (PAC) injection range from 0.31 to 3.78 mills/kwh depending on the type of coal used and the control technologies already in place. Engineering cost studies will be conducted to provide updated estimates of capital and operating expenses for PAC and innovative mercury retrofit control technologies. These updated costs will take into account the latest information available on the type of coal used and air pollution control systems in place. As part of this effort, research is planned to develop the methodology and data required to quantify the incremental mercury control costs for various multi–pollutant control options. NRMRL and DOE are coordinating with utility companies and technology vendors to test promising mercury and multi-pollutant control technology options in the field. The DOE has already solicited proposals. Their main role will be to select the test sites based on proposals submitted and provide funds for testing; industry will co-fund by providing the equipment and power plant upgrades, and NRMRL will play a lead role in collecting information on mercury emission levels both before and after the control device. More information on the activities of DOE and EPRI are discussed in Chapter 4.0. Finally, ORD will work with OAR to evaluate other mercury control options feasible for the electric utility industry, such as changes in dispatch patterns and fuel mix.

Increased testing and evaluation of mercury continuous emission monitors. A need exists to evaluate the performance and application of continuous emissions monitors (CEMs) to measure total mercury and the species of mercury present in combustion emissions even at very low concentrations. The ability to evaluate the performance of control technologies, determine compliance with regulations, and better characterize source emissions to support risk assessments requires CEMs that are capable of accurately and reliably quantifying both total mercury (Hg) as well as the speciated forms of Hg emitted from combustion sources, particularly at trace levels. Currently, total mercury CEMs are commercially available and widely used in Europe and their performance accepted. However, acceptable performance in the U.S. cannot be assumed, as pollution control device configurations in the U.S. vary greatly from those found in Europe. These CEMs are still susceptible to measurement interferences from combustion gases such as SO_2, hydrogen fluoride, HCl, and NO_x. In addition, most units are not capable of measuring the particulate-bound mercury component. As a result, PM is routinely filtered out, and remains unmeasured.

While there are no commercially available units that directly measure the various mercury species, significant strides have been made over the last few years. Many total gaseous mercury CEMs can be used to indirectly measure mercury species (the elemental and oxidized forms) by determining the difference between the elemental mercury and total gaseous mercury. This difference is recognized

as the oxidized form. Separate mercury measurements are made before and after the conversion step in order to calculate the oxidized form ("speciation by difference"). Several vendors are currently attempting to develop a mercury CEM that is capable of differentiating the species of mercury. Research is needed to identify the appropriate methods of measuring total mercury and the mercury species (the chemical forms of Hg) in combustion system flue gases. ORD's Environmental Technology Verification Program is planning to verify CEM performance against vendors' claims.

Research is needed to: (1) investigate the biases associated with total and speciated mercury measurements, particularly those associated with particle-bound mercury and the effects of interferences; DOE is sponsoring research to investigate sample conditioning techniques that address bias associated with speciated mercury measurements (by difference) and reactive particulate matter; and (2) evaluate the performance of total and speciated CEMs through both pilot-scale and field testing. Research also needs to be performed to determine if one method will work for all combustion sources or whether different methods must be used, and evaluate whether continuous measurements of mercury can confirm the effectiveness of feed limitations and thereby reduce compliance costs (*i.e.,* prove that emissions levels have been met without costly sampling of input stream). NRMRL is working with DOE in this area and will support field evaluation of the techniques identified under item 1 above.

Improved characterization of, and management approaches for, mercury controls residuals. There is a need to characterize mercury-contaminated residuals from air pollution control systems and, if needed, determine the cost and performance of technologies that can stabilize the residuals before they are sent for land disposal. Use of sorbent injection technologies to control emissions at electric power plants typically results in residues, which are either used as byproducts or are disposed. The total generation of coal combustion residues in 1998 was ~108 million tons, with ~77 million tons landfilled and ~31 million tons utilized. OSWER has indicated that composition data characterizing the different residues, as well as data on the composition of leachate are needed for total and speciated mercury, arsenic, and other toxics in these residues. These data are needed for calculating the mass balance flows associated with the management of mercury-contaminated residuals from coal-fired power plants.

No information is currently available on the potential life-cycle environmental burdens resulting from volatilization of mercury from byproducts and disposed residues. In order to ensure the mercury is not simply released into soil or groundwater, or subsequently released in air, research is needed to: (1) characterize any releases associated with the residues, and (2) develop ways to correctly manage the residues, including stabilizing the mercury before it is sent for land disposal, to prevent any subsequent release of mercury back into the environment. Research will focus on those waste management practices that are suspected of having the greatest potential for release of mercury including utilization of mercury containing residues in cement and wallboard production and production, and application of asphalt. The results from this research will provide a better set of data characterizing the various residue types and an improved understanding of the ultimate fate of mercury in the various practices in use to manage residuals from coal-fired power plants.

NRMRL will take the lead to synthesize results from the research described above including data generated by other federal agencies, academia and industry *(ORD does not plan to conduct research to evaluate improved techniques to clean coals prior to combustion; however, results of any research conducted by other federal agencies or private industry will be included in the integrated outputs*). Concise summaries of technology costs and performance will be provided to OAR and other interested stakeholders to assist them in evaluations of alternative mercury emission reduction options. These integrated research summaries will include information on how to control the various forms of mercury emitted and how integrated combinations of technologies can be used to simultaneously control mercury and other air pollutants of concern.

5.6.1.4 Research Results

Results from this research will provide improved data on the cost and performance of control technologies and other risk management options capable of reducing mercury emissions from priority combustion source categories (*e.g.* coal-fired utilities). OAR, OW, OSWER, and other Program Offices will use the data and information from this research to support regulation development for combustion sources where the Agency has a statutory responsibility to address mercury emissions. This work will also help states, Regions, and the private sector determine how specific technologies or approaches can be used to meet emissions standards or voluntary reduction targets that have been negotiated with EPA.

5.6.1.5 Measures of Success

Researchers hope to advance the following:

- Identification of the combustion conditions that have the most significant impact on the species of mercury formed in coal-fired utility boilers.
- Development of innovative mercury and multi-pollutant control systems that remove 70 to 90 percent of mercury at the lowest possible costs.
- Identification of viable approaches to measure both total mercury and species of mercury.

- Full characterization of the releases or emissions of mercury from waste management and utilization practices.
- Completion of successful demonstrations, at full or large pilot-scale, of innovative options to reduce mercury emissions from coal-fired utility boilers.
- Development of the most up to date information on the costs of mercury and multi-pollutant control options to support regulatory decisions.
- Production of a handbook on mercury controls to support implementation of regulatory requirements. This handbook will summarize information on the relative performance and cost of reducing mercury emissions using pretreatment approaches, flue gas cleaning technologies or combinations of these approaches with other air pollution control systems (co-control).

5.6.1.6 Preliminary Performance Goals

- By 2003, produce a comprehensive summary report (capstone report) documenting the performance of devices used to continuously measure total or species of mercury.
- By 2004, produce a technical assessment of the life-cycle implications of mercury-contaminated residues from air pollution control systems including the cost and performance of any required stabilization technologies.
- By 2005, complete comprehensive assessment of the capability of mercury control technologies and other risk management options (*e.g.* fuel switching) to achieve reductions from 70 to 90 percent in the most cost-effective manner (lowest $ cost per unit of pollutant removed).

5.7 RISK MANAGEMENT FOR NON-COMBUSTION SOURCES

5.7.1 Key Scientific Question

What is the magnitude of contributions of mercury releases from non-combustion sources; how can the most significant releases be minimized?

5.7.1.1 Background

While available data on the use and release of mercury in the non-combustion source category are limited, some available data indicate the total disposition of mercury by various segments of this category in the United States. In 1995, this category consumed 436 tons of mercury and contributed about 13 percent (20 tons) to U.S. mercury emissions. In the same year, over 12.2 million metric tons of mercury-bearing hazardous wastes were generated (EPA, 1998f), and an estimated 227 tons of mercury were disposed of in municipal landfills as part of mercury-bearing solid wastes. (EPA, 1997a)[1]

Because of the wide variety of sources and difficulties in measuring mercury emissions, estimates for some U.S. sources are believed to be low. However, these sources generally have low stacks or vents (and in some cases release soluble mercury compounds, such as $HgCl_2$ or even methylated mercury compounds) that may result in higher rates of local exposures per unit emissions compared to combustion sources. The numerous anthropogenic activities that use mercury produce mercury-bearing wastes and consumer products (including bulk elemental mercury) will pose a long-term threat to the environment if not disposed of properly. On a national scale, the magnitude of releases of mercury to soils and water by non-combustion sources appears relatively small. However, current and past releases are the sources for local "hot spots" of mercury contamination, and any significant releases from these hot spots need to be minimized.

5.7.1.2 Program Relevance

As reflected in the *Draft EPA Action Plan for Mercury* (Federal Register, 1998), the Agency proposes to reduce mercury releases from non-combustion sources using a number of approaches, including regulations (*e.g.,* Maximum Achievable Control Technology for chlor-alkali plant emissions) and promotion of voluntary activities by industry to reduce mercury use (*e.g.,* mercury takeback programs). Site- and facility-specific problems are being addressed by EPA Regional Offices. In some cases, improved characterization of mercury sources is needed prior to selecting options for reducing releases. The results of improved approaches to characterizing and reducing releases in the U.S. will carry over to the rest of the world, as evidenced by a number of EPA activities undertaken with other countries to enhance emissions reductions. Research described in this section supports a number of these important Agency activities.

5.7.1.3 Prioritized Research Needs

This section describes major remaining research activities to manage mercury releases from non-combustion sources, encompassing all non-combustion activities over the anthropogenic life cycle of mercury from extraction and refining through use to disposal. Releases of mercury to any environmental medium (air, ground or surface waters, or soil) are included. The scope of this section covers three phases of non-combustion risk management research:

- *Characterization of the mercury life cycle in human activities (Phase I).*
- *Improved understanding of mercury releases from sources and sinks (Phase II).*

- *Approaches for minimizing mercury releases from non-combustion sources (Phase III).*

While the scope of research activities in this section is broad, in keeping with the general approach of this strategy the research in this section will address only the most significant information gaps. Factors to be used in determining relative significance include the magnitude and uncertainty associated with characterizing and controlling releases to determine their risk, as well as the cost and effectiveness of characterization and control techniques. Also, a phased approach of progressively focused, in-depth studies will be used to maximize the impacts of the research program. In some cases, work will have to progress through all three phases. In other situations, the significance of an issue is well enough understood to proceed immediately to later phases. For example, ORD started investigating improved treatment options for hazardous waste disposal in FY 1999.

Because of the high EPA priority on management of mercury releases from combustion sources, studies of non-combustion sources will be limited through at least FY 2002. Therefore, some of the research needs described in this section may not be addressed until FY 2005 or beyond. ORD has organized its non-combustion risk management research program into project areas based on source type. Research in FY 2001 and FY 2002 will focus principally on source emissions characterization, process waste and mercury stockpile disposal, and options for reducing mercury use. During this period, characterizations of the mercury life cycle in human activities and its associated mercury releases should help to further focus research in these areas in FY 2003 through FY 2005. The significance of mercury from contaminated media such as sediments and mining residuals should also be better understood by FY 2002, allowing ORD to plan research activities in these areas for FY 2003 through FY 2005.

Characterization of the mercury life cycle in human activities (Phase I). There is a need to conduct a preliminary characterization of the mercury life cycle. The purpose of this activity is to understand the current flow of mercury in the United States from production to disposal, and to identify the significant release points during its life time. The results of this work will focus further ORD's releases characterization and control research. It should also identify human activities that have resulted in areas of major soils or sediments contamination.

Two activities are currently planned in this area:

- Evaluation of mercury use in the industrial sector to determine opportunities for reducing environmental impacts through source reduction;
- A preliminary inventory to re-evaluate releases data and identify the non-combustion sources with the most significant releases. The resulting "significant" sources will be characterized in more detail (see Phase II).

The evaluation of mercury use will update existing models of mercury flow in United States commerce. Besides helping to identify source reduction opportunities, it will also provide the Agency with basic information to create a supply and demand model for mercury in the United States. Such a model could be used to determine how economic and regulatory conditions might alter the flow of mercury in the United States. Such futuristic scenarios would also be an important additional contributor to focusing ORD's mercury research program. Because of the current emphasis placed on air emissions sources by the Agency, ORD initial releases inventory work will start in this area. ORD will work with the Office of Air and Radiation (OAR) to update available screening inventories of source emissions, such as that produced in *The Mercury Study Report to Congress*. By FY 2002, ORD plans to have conducted sufficient preliminary evaluations of mercury emissions to refine research priorities for Phases II and III.

Improved understanding of mercury releases from sources and sinks (Phase II). A need exists to better characterize mercury releases to the environment. While mercury releases are well characterized from some sources, that is not the case for all. For example, there is uncertainty about the magnitude of both elemental and speciated mercury air emissions from some sources that were identified in *The Mercury Report to Congress* as having releases below 10 tons/year. In many cases these uncertainties arise because good sampling or analytical techniques do not exist. In other cases, sufficient releases data have not been collected. ORD mercury releases characterization studies are intended to develop better sampling or analytical techniques on a source-specific basis, and to sample a very limited number of sources to better characterize their emissions. This releases characterization research will be carried out on a particular source type if sufficient data already exist to show it to be a potentially significant source, or if the results of Phase I so indicate.

NRMRL is currently targeting emissions characterization studies from: (1) mercury-cell chlor alkali plants (MCCAPs) and (2) municipal landfills. MCCAPs were identified because of the large discrepancy between their annual mercury makeup (about 160 tons/year) and their estimated 7.1 tons/year in mercury releases (EPA, 1997a). Mercury emissions from municipal landfills will be studied as part of an Agency program addressing PBT emissions from municipal landfills. While existing data suggest that landfills may not be a major source of inorganic mercury, the data also suggest that methylated mercury compounds may be emitted. Other sources of mercury air emissions that may require characterization include the oil and petroleum industry. The significance of their emissions will be considered along with others from non-combustion sources in the preliminary emissions inventory work of Phase I to determine if emissions characterization research is needed for them in Phase II.

Mercury releases can also occur in the form of solid waste and water effluent streams. Mining effluents are believed to be the most significant mercury effluent source, causing regional contamination problems. Mercury-bearing effluents from mining appear to cause significant sediments contamination and associated fish advisories in receiving rivers and lakes, particularly in the western United States. Preliminary studies will be conducted to better characterize mercury releases from mines in order to determine whether the problem is significant enough to warrant control research. ORD will continue to work with the Mercury Task Force (MTF) to determine other significant mercury effluent sources.

Waste streams pose more uncertainties. It is difficult to characterize mercury-bearing wastes, and how they release mercury under the range of environmental conditions found in disposal facilities. Because of this, and as part of its support of the EPA Office of Solid Waste (OSW) rulemaking to revise the Land Disposal Restrictions (LDRs) treatment standards for mercury-bearing wastes, especially "high subcategory" mercury wastes (*i.e.,* wastes containing over 260 ppm total mercury), ORD is evaluating improved characterization techniques for mercury in wastes. Both sediments and soils can be sources of mercury releases to air or surface waters. (Ground water is not viewed as a significant exposure pathway). Sediments are a significant sink for air- and water-borne mercury releases. Sediments are also host to the base of the food web that extends through aquatic organisms to land-based wildlife and humans. There are also a number of sites with significant contaminated mercury in soil, and while elemental mercury in soil is not highly soluble, it may be volatilized, or methylated and enter the food chain.

Approaches for minimizing mercury releases from non-combustion sources (Phase III). There is a need to identify alternate approaches for minimizing mercury releases. Mercury releases can be minimized by reducing the use of mercury or by use of end-of-pipe controls, including waste treatment. NRMRL will study both approaches, focusing on major release sources. Source reduction opportunities will be identified in the mercury-use study in Phase I. Selections will be based on release potential, industry interest in voluntary reduction, and other factors. For these selected sectors, ORD will conduct research to advance the reduction of mercury use. This research, done in collaboration with industry where possible, will include application of life cycle analysis (LCA) tools and studies of innovative source reduction processes.

Sources requiring mercury control research will be identified based on the magnitude of the release, availability of cost-effective control techniques, and Agency priorities. For example, if releases of mercury are significant from MCCAPs or mining, then control research may be required because cost-effective means of controlling non-point source releases is often difficult. Treatment technology research on hazardous wastes bearing high concentrations (>260 ppm) of mercury is an OSW priority because they are currently investigating alternatives to incineration and retorting. The research needs, collaboratively identified with OSW, include improved waste characterization and alternative technology research and demonstration.

The ultimate disposal of mercury stockpiles is also of concern. Large stockpiles already await disposal. For example, The Department of Defense (DOD) currently manages a mercury stockpile of approximately 4,400 metric tons. The total amount of stockpiled mercury in the United States will be increasing as the number of federal, state and local programs to reduce mercury use and to recycle mercury products increase. Environmentally safe disposal alternatives for elemental mercury have not been fully evaluated in terms of long-term effectiveness and cost. ORD will work with the EPA Mercury Task Force and outside stakeholders to determine major research needs and to address those where expertise is available.

Three approaches are available for the management of mercury in sediments: capping, in-situ methods, and dredging followed by confinement or treatment. Natural processes affecting Hg in this environment must also be understood. NRMRL has an established contaminated sediments research program and many of its research findings for metals are applicable to mercury. However, research is needed on in-place management of mercury-contaminated sediments that focuses understanding and enhancement of processes that sequester mercury from the food web. These processes include physical disruption of the exposure path (*e.g.,* clean sediment deposition), chemical alteration of the mercury to less bioavailable or biotoxic forms, and biological transformation or sequestration. Particular emphasis will be given to disrupting the formation of methyl-mercury.

Research on remediation options for soils contaminated with mercury is a lower relative priority, although remediation of these sources must ultimately be addressed. Contaminated soils remediation may be of high priority on a site-specific basis. Remediation options for such sites are under development by others, such as DOE, and should continue. Whenever possible, information on remediation options for soils should be collected during mercury remediation/treatment research on waste streams, mining, and contaminated sediment, and during more broadly-scoped remediation research for metals in soils.

5.7.1.4 Research Results

Results from this research will contribute to an improved understanding of mercury releases from non-combustion sources, and where appropriate, sinks (*e.g.,* contaminated sediments, abandoned gold mining sites). While emissions from coal-fired utilities and other combustion sources are fairly well understood, this is not the case for other sources

of mercury. The Program Offices, Regions, and states will all benefit in terms of regulatory and voluntary actions for mercury with a better understanding of the releases from a variety of sources. Work will also be targeted at approaches that minimize mercury releases into the environment, including the ultimate disposition or retirement of excess metallic mercury stocks.

5.7.1.5 Measures of Success

As indicated above, research on the non-combustion risk management research area starts at a modest level, likely expanding in FY 2004 as the need for combustion risk management research declines. The ability of ORD to accomplish all the research described in this section is resource dependent and will likely need to continue past FY 2005 in order to reach the measures of success described below. In addition, Phase I research during the early years of the program may identify higher priority research needs, and therefore some research activities described here could be dropped altogether. Consequently, the measures of success described below are those currently identified for priority research needs, but these measures are subject to change as our understanding of non-combustion mercury releases grows.

1. Characterization of the mercury life cycle in human activities (Phase I)

- Assessment of anthropogenic mercury use to identify major opportunities for reducing use and/or releases.
- Assessment of the relative significance of mercury emissions from anthropogenic sources in the United States.

2. Improved understanding of mercury releases from sources and sinks (Phase II)

- Identification and/or evaluation of technologies and techniques that provide improved MCCAP facility emissions measurements.
- Improved characterization of air emissions from priority source categories, such as MCCAP, landfills and oil and gas processing facilities.
- Identification of mining waste types that contribute most to mobile mercury.

3. Approaches for minimizing mercury releases from non-combustion sources (Phase III).

- Improved understanding of the effectiveness and cost of vendors' innovative technologies for control of air emissions from high priority source categories.
- Assessment of the effectiveness, cost, and environmental impacts of solidification/stabilization processes as applied to mercury-bearing hazardous wastes.
- Recommendations for improved techniques for determining the mobility of mercury in various hazardous waste treatment residuals.
- Evaluation of several pollution prevention approaches for reduction of mercury use, and determination of the reduction in adverse environmental impacts.
- Improved understanding of the processes that control mercury transport and re-transformation in sediments.
- Development and/or evaluation of three technologies to control mercury transport or bioavailability at abandoned mining sites.
- Assessment of the options for ultimate disposal of mercury stockpiles.

5.7.1.6 Preliminary Performance Goals

Current GPRA Annual Performance Goals (APG) for this program reflect the phases of activities of the program (FY 2003 and FY 2006 APGs) and the anticipation that the program should take about 10 years to complete. The APGs are:

- By 2003, provide technical resource documents to public and private decision makers and other stakeholders on the magnitude of releases of mercury from non-combustion sources and recommend methods for characterizing emissions for priority sources.
- By 2006, provide technical resource documents to public and private decision makers and other stakeholders on options for cost-effectively reducing releases from priority non-combustion sources including "low tech" approaches for reducing mercury emissions.
- By 2007, provide technological transfer of control and mercury reduction technologies for combustion and non-combustion sources.
- By 2009, provide an authoritative set of risk management options to public and private decision-makers and other stakeholders for priority non-combustion sources of mercury releases to the environment.

5.8 ECOLOGICAL EFFECTS AND EXPOSURE

5.8.1 Key Scientific Question

What are the risks associated with methylmercury exposure to wildlife species and other significant ecological receptors?

5.8.1.1 Background

Recent scientific progress has led to a greatly improved understanding of mercury fate and transport in the environment and its toxicity to a wide range of ecological receptors. This work has focused attention on the aquatic

environment and, in particular, on consumption of methylmercury contaminated fish by fish-eating birds and mammals. A review of this material is provided in "An Ecological Assessment for Anthropogenic Mercury Emissions in the United States," Volume VI of the *Mercury Study Report to Congress* (EPA, 1997a). The report primarily assessed the impacts of mercury and methylmercury on wildlife and did not focus on fish or other biota.

Despite this progress, however, substantial scientific uncertainties remain that limit efforts to characterize the ecological risks associated with anthropogenic mercury emissions. The research areas prioritized below reflect EPA's need to assess the risk of methylmercury to fish-eating wildlife and to calculate water-based wildlife criteria for mercury that are protective of fish-eating wildlife populations. The Agency recognizes that this prioritization could change substantially as new information about mercury exposure and effects becomes available. In many cases it is difficult, and sometimes counterproductive, to consider chemical effects apart from exposure. The emphasis of this effort is on research needs for ecological effects assessments and ecological risk assessment. Section 5.5 focuses on the fate and transport of mercury. Section 5.5.1.3 includes research on aquatic and terrestrial transport, transformation, and fate, and will supply exposure data concerning ecological endpoints. Results from the effects and exposure research, along with distributional assessment methods, will produce a state-of-the-art ecological risk assessment for mercury.

5.8.1.2 Program Relevance

Mercury pollution of aquatic systems is a national problem. At the end of 1998, fish consumption advisories due to unacceptable levels of mercury existed in 40 States. In some cases, these advisories can be traced to point sources of mercury. Increasingly, however, non-point source mercury contamination has resulted in large-scale pollution of entire ecosystems, with possible impacts on both humans and wildlife. Perhaps the best known example is that of the South Florida Everglades, which is home to the endangered Florida panther. High levels of mercury and methylmercury in tissues of deceased animals have led to the suggestion that methylmercury is a contributing factor in the decline of the panther population. It is the responsibility of EPA's Regional Offices to deal with such problems. Seeking technical assistance, the Regions have engaged the Office of Research and Development (ORD), the Office of Water (OW), the Office of Air Quality Planning and Standards (OAQPS), and others, to address this concern.

EPA has the responsibility under the Clean Water Act (Section 304(a)(1)) to develop water quality criteria that are protective of wildlife that may be exposed to chemical pollutants in water. The first effort to develop a wildlife criterion for mercury was undertaken by OW in support of the Great Lakes Water Quality Initiative (GLI). The GLI was promulgated as a rule, and as such, constitutes a powerful legal mandate. States in the Great Lakes basin have either submitted or are drafting strategies for compliance with the GLI. EPA Regions (Regions II, III, and V) that adjoin one or more of the Great Lakes are primarily responsible for implementation of the GLI, including the wildlife criteria for mercury. Uncertainties regarding wildlife exposures to methylmercury and the subsequent effects of those exposures have greatly complicated these efforts. This research area will serve to strengthen the scientific credibility of water quality criteria for mercury and procedures for implementing those criteria in watersheds throughout the Nation.

5.8.1.3 Prioritized Research Needs

The major research needs are identified below in order of their relative priority. Each is accompanied by a brief narrative to describe the type of work required to address these needs.

- *Improved understanding of methylmercury toxicity effects on avian and mammalian wildlife.*
- *Refined ecological assessments for avian and mammalian wildlife risks.*
- *Improved understanding of ecological impacts of methylmercury on avian and mammalian wildlife.*
- *Improved understanding of ecological impacts of methylmercury on non-avian and non-mammalian species.*
- *Identification of interactions among methylmercury and other chemical and non-chemical stressors on all ecological receptors.*

Improved understanding of methylmercury toxicity effects on avian and mammalian wildlife. A need exists for controlled laboratory studies of methylmercury disposition and effects in wildlife species or appropriate surrogates. Current procedures for calculation of a wildlife criterion (WC) for mercury are based on an extremely limited toxicity data set. Moreover, in the calculation of a wildlife reference dose (RfD) for methylmercury, there is a need to use several uncertainty factors (*e.g.,* species-to-species, LOAEL-to-NOAEL), each of which is supported by very limited data. Research should be conducted to characterize the kinetics of methylmercury uptake and disposition, and the importance of hepatic demethylation as a route of elimination. Additional research is needed to develop and refine assessments of risk based on mercury and methylmercury residues in the tissues of exposed wildlife and their prey. Tissue residue-based assessments have the potential to avoid many uncertainties associated with assessing mercury and methylmercury exposure. However, research is needed to support the development of reliable tissue-residue response relationships, including: identification of critical target tissues, assessment of

interspecies and intraspecies differences in sensitivity; and the development of Physiologically-Based Pharmacokinetics (PBPK) dosimetry models for sensitive and highly exposed species.

Refined ecological assessments for avian and mammalian wildlife risks. The research above will contribute to improve assessments of mercury risk to wildlife and other ecological receptors. It is possible, however, to identify research that focuses directly on the risk assessment process as a means of addressing specific problems. Given the relatively small number of avian and mammalian wildlife species that prey heavily on fish, it is reasonable to collect species-specific information that would lead to improved exposure characterizations. This would include characterizations of exposure variability due to seasonal changes in location and dietary choice. In risk characterization, probabilistic and distributional methods must be applied to both exposure and effects information. Analyzing the distribution or range of a given parameter (*i.e.,* toxic effects, fish size, food consumption) will reduce uncertainty. For example, point estimates of effect could be replaced by information that would permit the calculation of effects benchmarks and statistical confidence limits.
Revising laboratory experimental designs to produce dose-response curves with EC10, EC20 values will enhance the use of probabilistic methods. Existing ecological risk assessment methods are, in general, poorly adapted for use with compounds that bioaccumulate and are biotransformed. New assessment methods must be developed to accommodate these factors, perhaps in concert with more site-specific or residue-based regulatory procedures. It is expected that future exposure research efforts will be focused on identification of aquatic systems that have characteristics for significant methylmercury production. This work should be complemented by research on other factors that contribute to variability in bioaccumulation of methylmercury by fish. Bioenergetics-based bioaccumulation models for fish must be developed to provide probabilistic residue estimates within and among trophic levels.

Improved understanding of ecological impacts of methylmercury on avian and mammalian wildlife. Using a "weight of evidence" approach, the authors of the *Mercury Study Report to Congress* reached the conclusion that mercury originating from airborne sources has had an adverse impact on several avian and mammalian wildlife species. Field data required to confirm or refute this suggestion are, however, lacking. A need exists to conduct field research on wildlife species. This research would be complementary to the laboratory studies described previously. Critical questions that would be addressed by this work include: (1) are there species that, because they possess specific attributes, could function as sentinels for mercury contamination? (2) do field data support projections of increased risk to wildlife living in proximity to mercury emissions sources? and, (3) can population attributes (*e.g.,* age-class structure) be used to indicate adverse effects on individuals? A critical question for establishing a WC value for mercury is whether a population of animals can withstand adverse effects on a limited number of individuals. Population models for relevant species must be developed to predict the probability of localized extinction due to impacts on critical population parameters (*e.g.,* reduction in the per capita growth rate due to reproductive effects), as well as time-to-recover under different exposure reduction scenarios. Finally, it is important to determine whether sublethal exposures to methylmercury can contribute to the demise of endangered wildlife species.

Improved understanding of ecological impacts of methylmercury on non-avian and non-mammalian species. Based largely upon exposure considerations, it may be concluded that piscivorous avian and mammalian wildlife species are most at risk from adverse effects of environmental mercury. This analysis presumes, however, that the toxicological sensitivity of all animals to mercury (on a delivered dose basis) is approximately the same. The possibility exists that there are animals that, because of increased sensitivity, experience adverse toxic impacts at relatively lower tissue-residue burdens. Research focused on early life stages of fish has revealed toxic impacts at waterborne methylmercury concentrations previously thought to have no effect on fish. This work should be expanded and similar research conducted on other key aquatic species. Additional work is needed to evaluate mercury and methylmercury toxicity to some terrestrial species, especially those that inhabit forest soils and soil drainages. A second possibility is that there are non-wildlife aquatic or terrestrial species that, because of unusual bioaccumulation or food web relationships, experience mercury exposure comparable to that of piscivorus wildlife.

Identification of interactions among methylmercury with other chemical and non-chemical stressors on all ecological receptors. Mercury often co-occurs with other chemical stressors, and in particular with compounds that tend to bioaccumulate in aquatic biota, including polychlorinated biphenyls (PCBs) and 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD). In mixture studies with mink, methylmercury and PCBs acted together, resulting in toxic effects greater than those that could be attributed to either chemical individually (EPA, 1997a). Additional studies of this type are needed to define the nature of these chemical interactions. Field research is also required to investigate the potentially modifying effects of both chemical and non-chemical stressors. Perhaps the best example to date is that of the Florida panther. While it can be shown that mercury residues in dead panthers exceed levels found in experimentally intoxicated cats, a multitude of other factors complicate any assessment of risk. Included among these factors are habitat fragmentation and a lack of genetic diversity.

5.8.1.4 Research Results

Results from this research will be used by NCEA in refined mercury ecological risk assessments that will support future policy decisions on safe mercury levels for fish, birds, and other animals. Data that are developed will contribute to an improved sensitivity analysis and assist in reducing uncertainty in a number of areas pertinent to mercury effects and exposures in ecosystems. Using these refined risk assessments will help OW provide more informed guidance on methylmercury in water bodies. This work will also assist States in making decisions on action levels for mercury total maximum daily loads (TMDLs).

5.8.1.5 Measures of Success

Researchers hope to advance the following:

- Successful characterization of the toxicokinetics and toxicodynamics of methylmercury in piscivorous avian and mammalian wildlife.
- Development of probabilistic ecological impact assessment procedures for mercury that explicitly recognize relevant natural processes.
- Characterization of the impact of methylmercury on piscivorous wildlife populations at local, regional, and national scales.
- Reduction in the uncertainty in evaluation of potential adverse effects on fish.
- Evaluation of the potential for adverse impacts on fish and other non-avian, non-mammalian ecological receptors.
- Identification and characterization of important interactions of mercury with other environmental stressors.

5.8.1.6 Preliminary Performance Goals

GPRA performance goals have been identified for the ecological effects and exposure research area based on the above Measures of Success. They are preliminary in nature and will be revised and adjusted as part of the implementation of the *Mercury Research Strategy*. A preliminary set of performance goals is offered below. The performance goals are:

- By FY 2003, prepare a report characterizing the toxicokinetics and toxicodynamics of methylmercury in avian species.
- By FY 2005, prepare a report on regional variability factors leading to a probabilistic ecological risk assessment on methyl mercury.
- By FY 2007, conduct a regionally based probabilistic ecological risk assessment of the effects of methyl mercury on representative avian and wildlife species.

5.9 HUMAN HEALTH EFFECTS AND EXPOSURE

5.9.1 Key Scientific Question

What critical changes in human health are associated with exposure to environmental sources of methylmercury in the most susceptible human population? How much methylmercury are humans exposed to, particularly women of child-bearing age and children among highly-exposed population groups; what is the magnitude of uncertainty and variability of mercury and methylmercury toxicokinetics in children?

5.9.1.1 Background

Health Hazards

The initial step in the risk assessment process is identification of health hazards. Earlier reference doses (RfDs) for methylmercury were based on neurological changes in the adult. In 1994, EPA announced a new RfD based on methylmercury's adverse effects on children's neurological development. Other federal agencies (e.g., FDA) continue to base their regulatory activities on effects in adults or have developed assessments (e.g., ATSDR's Toxicology Profile on Mercury [ATSDR, 1999]) aimed at a fetal protective dose based on epidemiological studies of other populations. Between 1995 and 2000, deliberations have focused on the appropriateness of specific epidemiological investigations for risk assessment. Following an FY 1999 Congressional budget appropriation for the National Academy of Sciences (NAS) to conduct a study on toxicological effects of methylmercury, a report was released from the NAS in July 2000 (NRC, 2000). This effort involved a review of the health research on mercury conducted since the completion of the Mercury Study Report to Congress released in 1997. The NAS Committee's report recommended the following:

- That the value of EPA's current RfD for methylmercury, 0.1 micrograms per kilogram of body weight per day, is a scientifically justifiable level for the protection of public health.
- Developmental neurotoxicity of methylmercury is the critical endpoint for setting an RfD, and the Faroe Islands study should be used as the critical study for the derivation of the RfD.
- That estimates of a benchmark dose lower bound (BMDL) of 58 parts per billion (ppb) of mercury in cord blood (corresponding to a BMDL of 12 parts per million [ppm] of mercury in hair) is a reasonable point of departure for deriving the RfD.

- To calculate the RfD, the BMDL should be divided by uncertainty factors that take into consideration biological variability when estimating dose and methylmercury database insufficiencies. An uncertainty factor of at least 10 was supported by the NAS report.
- The NAS report recommended additional investigation into the following areas:

  1. The impact of methylmercury on the prevalence of hypertension and cardiovascular disease in the United States. Likewise, reproductive effects of methylmercury exposure are not fully understood.
  2. The relationships between low-dose exposure to methylmercury throughout the life span of humans and animals and carcinogenic, reproductive, neurological, and immunological effects.
  3. The potential for delayed neurological effects resulting from mercury remaining in the brain years after exposure.
  4. The emergence of neurological effects later in life following low-dose prenatal methylmercury exposure.
  5. The mechanisms underlying methylmercury toxicity.

Dose-Response Assessment

The NAS report (NRC, 2000) recommended that an uncertainty factor of at least 10 be used when developing an RfD from a BMDL. The committee recommended that an uncertainty factor of 2 to 3 be applied to a central tendency estimate of dose derived from maternal hair, or a factor of about 2 be applied to a central tendency estimate of dose derived from cord blood to account for interindividual pharmacokinetic variability in dose reconstruction. This recognized variability is based on the current understanding of person-to-person variability among adults in toxicokinetics of methylmercury. Because the developing nervous system is considered the critical endpoint for development of an RfD or equivalent values (*e.g.,* ATSDR's Minimal Risk Level), there is a need for additional data on toxicokinetics and variability in toxicokinetics in the pregnant woman/fetal pair. Most of the available data were developed during studies of adults, especially adult males. Pregnancy is known to introduce differences in the kinetics of methylmercury.

The adverse effects of methylmercury on neurodevelopment continues postnatally (*e.g.*, myelination, synaptogenesis, and glial cell formation). These processes, particularly myelination, continue for a number of years postnatally making the young child, as well as the fetus, vulnerable to developmental changes caused by methylmercury exposures. Methylmercury is known to be excreted in breast milk making the nursing mother/infant pair an additional sensitive population. Additional data to identify the range of variability in estimates of maternal dose and the infant dose produced by these exposures is needed. Likewise, the kinetics of methylmercury in children are fundamentally not known. As noted above, young children may have additional health changes beyond those recognized among adults.

Whether or not similar doses in adults and in children produce similar nervous system responses remains to be evaluated. Existing data from the poisoning outbreaks in Iraq and in Japan showed that children will develop the same symptoms of methylmercury poisoning similar to those developed by adults. It is unclear if children develop these responses at lower or higher doses of methylmercury than those which damage the adult nervous system. Likewise, additional research is needed to determine if there are additional endpoints, specific to postnatal exposure during childhood, associated with increasing exposure to methylmercury. Toxicokinetic models for methylmercury are available for adults. The *Mercury Study Report to Congress* indicated that research was needed to understand mercury and methylmercury partitioning in children from a toxicokinetic basis. Further studies of fish intake and methylmercury exposure among children were also cited as a research need.

Interactions with Other Chemicals, Age, and/or Forms of Mercury

Evaluation of data from the three major epidemiological studies (the Faroese, the Seychellois and the New Zealand cohorts) has been made more complex because methylmercury exposures occur from ingestion of fish. Fish contain chemicals that are beneficial to development (e.g., the omega three fatty acids) and others that are adverse to neurodevelopment (e.g., PCBs, other persistent bioaccumulative toxics such as dioxins). The understanding of how co-exposure to either the beneficial or adverse effects of these other chemicals is particularly limited in estimates of dose-response relationships. Initial data also reveal that prenatal exposure to mercury vapor causes alterations in both spontaneous and learned behavior in rodents. Co-exposure to methylmercury at levels (which by themselves did not alter these functions) served to potentiate these deficits when exposure to mercury vapor and methylmercury were combined. Additional research to evaluate the impact of co-exposures to mercury vapor (as occur from dental amalgams) and methylmercury from dietary consumption of fish are needed.

The third major area of interaction is between methylmercury exposures and age-associated changes. The NAS Committee reviewed preliminary data on the potential effects of early-developmental exposure to methylmercury on the functional status of aging animals. Data on occurrence of symptoms of survivors of Minamata disease indicated that health risks of methylmercury exposure could last a lifetime and may become exacerbated during the process of normal aging. Consequently, research is needed to determine the long-term implications of the neuropsychological and neurophysiological effects of low-

level methylmercury exposures. These studies should focus on issues that include:

- Critical periods for methylmercury effects: in utero or postnatal.
- Low-level dose-response relationships.
- Methylmercury demethylation in the brain following early methylmercury exposures.
- Synergistic effects of early methylmercury exposure and mercury vapor exposures.
- Neurodegenerative disorders related to methylmercury exposures.

The NAS report also described recent studies that found associations between exposure to methylmercury and impairments in the immune, reproductive, and cardiovascular systems. Both prenatal and postnatal exposures to methylmercury have been associated with immunological and cardiovascular changes. Levels of methylmercury exposure associated with these effects are as low as those producing adverse neurodevelopmental effects. In some cases, the exposures are even lower than those producing neurodevelopmental changes. Research using animal models and human populations having chronic, low-dose exposures to methylmercury is needed.

Although the developing nervous system is more sensitive to methylmercury than is the adult nervous system, the NAS report also questioned long held interpretations of blood and hair concentrations of methylmercury associated with adverse neurological effects. Recommendations on tolerable exposures for adults (e.g., EPA's pre-1994 RfD of 0.3 micrograms per kilogram of body weight per day, FDA's tolerable exposures, and the World Health Organizations [WHO] limits) are based on the assumption that paresthesias are the critical effect. Research carried out in the past decade have identified adverse effects (including changes in visual field, neuromotor disturbances, visual and auditory conduction velocities) at exposures less than those associated with paresthesias. Additional analysis of dose-response to methylmercury among adults is needed.

Human Exposures

As part of the discussions on the risk characterization for methylmercury, it was determined that young children are exposed to higher doses of methylmercury than are adults (e.g., approximately 1.5- to 2-fold or higher on a body-weight basis) (EPA, 1997a). Development of the nervous system postnatally includes processes (among others, myelination) that are adversely affected by methylmercury; however, it is uncertain how different exposure-response is for the young child in comparison with the fetus or the adult. Children may have different patterns of tissue distribution of mercury and methylmercury (i.e., biokinetic patterns) than adults. For these reasons, determining the dose-response to postnatal mercury and methylmercury exposures among children is critical.

Consumption of fish and marine birds and mammals represents more than 95 percent of the human intake of methylmercury. Within the United States, individual consumption of fish and seafood is highly variable. Approximately 1 to 2 percent of the U.S. population report eating fish daily, whereas about 10 percent rarely consume fish. The Mercury Study Report to Congress (EPA, 1997a) conducted extensive analyses of fish consuming habits and patterns among the general U.S. population and high-risk populations. To improve the human-exposure estimate on the basis of surveys of fish consumption, more study is needed within both the general population and high-end fish consumers. This work would examine specific biomarkers of mercury and methylmercury exposures (e.g., blood-mercury concentrations and hair-mercury concentrations).

Part of a strategy to meet the need for biomonitoring for mercury in the general population will be met by inclusion of blood and hair mercury analyses in the fourth National Health and Nutrition Examination Survey (NHANES IV). This survey will be large enough to produce estimates of the upper percentiles of mercury tissue levels in the general populations of women of child-bearing age and children. The survey will include dietary questions on type and frequency of fish consumption. Due to its statistical design, however, it will not be able to estimate the distribution of hair and blood mercury levels in highly exposed sub-populations including: Alaskan Natives, some Native American tribes, and people of Asian descent, as well as subsistence and sport fishers and their families, and others who consume large amounts of fish (e.g., some following "health conscious" diets). While data from similar populations in Canada will be useful in this connection, research is needed to fill this data gap because the Canadian data are largely focused on groups such as Native Canadians and subsistence fishers in remote locations.

5.9.1.2 Program Relevance

The practical importance of a separate pediatric RfD results from higher exposures (on a micrograms per kilogram of body weight per day basis) to methylmercury among children rather than adults. If children are both vulnerable and more highly exposed relative to body weight than are adults, children as well as the maternal-fetal pair are an important subpopulation. Identifying of which is of greatest concern includes factors such as the size of the population, severity of the effect, and relative vulnerability. Although the RfD for the young child may not be very different from an RfD that is protective of the fetus, policy statements would need to address the much higher intake (on a 0.1 micrograms per kilogram of body weight per day basis) of the young child. If research subsequently demonstrates that additional organ systems (*e.g.,* immunotoxiocity) are adversely affected at lower doses of mercury than is the case for neuro-developmental and neuro-behavioral changes, it may be necessary to revise the RfD to protect against immunotoxiocity. Likewise, it

may be of overall importance to understanding at-risk populations and to reassess what hair and blood mercury levels are associated with lower exposures than those producing paresthesia, long held to be the most sensitive adverse effect in adults.

Estimating the size of the "at risk" human population for methylmercury exposure requires data on how much methylmercury people consume from fish and seafood. Data on geographically determined variability in the concentrations of methylmercury in fish and seafood are critical to estimating local impacts of control technologies and pollution prevention efforts. This information also provides a baseline against which the impact of future environmental interventions can be assessed. In particular, there is controversy concerning the size of the U.S. population exposed at levels comparable to those in ongoing studies of fish-eating and wildlife-eating populations.

The Children's Health Executive Order 13045 (Federal Register, 1997) requires consideration of children as an "at risk" population. It is known that children experience one-to-two times higher exposures (on a body-weight basis) to methylmercury at comparable concentrations of methylmercury in fish. Because the nervous system continues to develop during at least the first six years of life, post-natal exposures to methylmercury may damage the nervous system after birth. It is not known whether young children are more like fetuses or adults with respect to CNS-based methylmercury toxicity. This combination of higher exposures and uncertainty with respect to vulnerability makes research on exposures, toxicokinetics, and effects of methylmercury on children a high priority.

5.9.1.3 Prioritized Research Needs

- *Improved understanding of mechanisms of developmental neurotoxicity from methylmercury.*
- *Improved understanding of persistent and delayed neurotoxicity resulting from developmental exposures to methylmercury.*
- *Identification of impacts from aggregate exposures and synergistic effects of methylmercury and other pollutants.*
- *Improved understanding of the modulation of immune system response from methylmercury exposure.*
- *Improved understanding of the effects on cardiovascular function as a result of methylmercury exposure.*
- *Biological monitoring for model development and improvement.*
- *Development of toxicokinetic data on methylmercury tissue distribution.*

Improved understanding of mechanisms of developmental neurotoxicity from methylmercury. A need exists to understand the mechanisms of developmental neurotoxicity. While methylmercury is a well-recognized developmental neurotoxicant in humans and animals, the critical mechanism(s) are still ill-defined. An improved understanding of the mechanisms of methylmercury's developmental neurotoxicity should be linked to exposure data in the form of biokinetic models, in order to provide an improved framework for the design of biologically based dose-response (BBDR) models. These models would need to include reliable predictions of adverse effects following prenatal, postnatal, and perinatal exposure scenarios.

Improved understanding of mechanisms of developmental neurotoxicity following exposure to mercury and methylmercury could greatly enhance interspecies extrapolation in the risk assessment of this environmentally persistent pollutant. It is necessary to understand and characterize children's risk because no readily available population exists for postnatal-only exposures. Mechanistic modeling of methylmercury-induced developmental neurotoxicity is predicated on the current and continuing research both in humans, *in vivo* animal models, and *in vitro* models where exposure and effects have been determined. This research provides the unique opportunity to expand understanding beyond theoretical models based upon developmental mechanisms of action for experimental data, and provide some predictability of effects following actual low-level exposures in developing humans.

Mechanistic understanding of methylmercury's developmental neurotoxicity has significant implications for other compounds and should help to define what developmental processes, endpoints, and time points may be especially sensitive to developmental perturbation. In addition, experimental evidence suggests that the effects of mercury and methylmercury exposure on the development of the nervous system and immune system may involve some common mechanisms (neurotrophic factors and cytokines). Mechanistic understanding will be highly important in determining the duration of exposure that is associated with adverse neurodevelopmental effects. Specifically, current concepts of RfDs are that these levels are safe if consumed over a lifetime. However, developmental windows of vulnerability are such that far shorter time periods (i.e., days, weeks) may be highly significant. Consequently, developmental RfDs may be far more briefer than life-time exposures. Mechanistic understanding will also contribute to clarifying co-exposure to other neurotoxicants, especially inorganic mercury, may need to be considered in determining tolerable exposures to methylmercury.

Improved understanding of persistent and delayed neurotoxicity resulting from developmental exposures to methylmercury. Another area of concern is the onset or exacerbation of neurological deficits in aging populations exposed *in utero* or as children. There are indications of this in the follow-up studies of the Minamata population wherein there is evidence that neurological dysfunction

among people who have been exposed to methylmercury becomes exacerbated with aging. This heightened diminution of function is greater than that attributable to either age or methylmercury exposure alone. Animal studies lend support to the conclusion that methylmercury can have delayed effects that are uncovered with age. Mice exposed during gestation and lactation to methylmercury who were normal at birth developed deficits in exploratory behavior and swimming ability at 1 month, and neuromuscular and immune effects as the animals reached 1 year of age. Monkeys exposed developmentally to methylmercury developed motor incoordination when they reached middle age. Monkeys exposed *in utero* and postnatally exhibited hearing deficits in middle age, which grew relatively worse during old age compared to controls, providing evidence for an interaction of aging and methylmercury exposure on auditory impairment. All of these observations are consistent with a hypothesis that early life or *in utero* exposure to methylmercury can have adverse long-term sequelae that may not be detected in childhood. It further suggests that exposure in adulthood that results in signs of mercury toxicity can result in an exacerbation of the effects of aging. Both mechanistic and descriptive studies are needed to understand the basis of these effects, and at what body burden they occur.

Identification of impacts from aggregate exposures and synergistic effects of methylmercury and other pollutants. A need exists to identify the risk assessment uncertainties following aggregate exposure to developmental neurotoxins. An improved mechanistic understanding of the developmental neurotoxicity of methylmercury is needed to assist in understanding the additive, subtractive, and synergistic relationships among other commonly occurring environmental pollutants (e.g., dioxin, PCBs, dibenzofurans). Human epidemiological data are often complicated by exposure to a combination of many pollutants (e.g., Great Lakes fish and marine mammals; fish of the North Sea), and more research is needed to characterize the neurotoxicity and immunotoxicity of aggregate exposures.

Improved understanding of the modulation of immune system response from methylmercury exposure. A need exists to improve the Agency's understanding of the toxicity of mercury and methylmercury to additional organ systems. Recent data suggest that exposure to mercury compounds through a number of routes can modulate immune responses. Immunomodulation is manifested as an adverse effect in three general areas: autoimmunity, immune suppression (with enhanced risk for infectious disease), and allergy. Specific research findings in these areas include:

- Autoimmunity. Mercury exposure in either experimental animal models or in humans has been shown to be a potent stimulus for the expression of autoantibodies and autoimmune responses in some susceptible populations. The risk for latent autoimmune diseases following low-level developmental exposure of children is largely unknown.
- Immune Suppression. Methylmercury has been reported to be a potent effector of immune suppression, including both humoral responses and natural killer cell activity. Humoral response consists of antibody production; natural killer cell activity protects against infectious agents. The subsequent effects of developmental exposure, at least in experimental animals, indicate that there is an increased risk, principally during the postnatal period, leading to increases in the number and severity of infections later in life.
- Allergy. Exposure to either organic or elemental mercury is a well-known environmental stimulus of allergic responses (*i.e.,* contact dermatitis) in humans and animals. These responses have been demonstrated in adults and children. There is, however, little clear evidence to date of age-related sensitivity either qualitatively or quantitatively.

These findings raise the following questions which need to be addressed: How does developmental exposure to methylmercury affect immune responses and susceptibility to disease? What components of the immune system are affected? Is there a critical window of opportunity? What are the dose-response relationships? What are the underlying mechanisms? How do answers to these questions compare to developmental neurotoxicity, another critical effect?

Susceptibility to immunotoxic effects may differ substantially across exposed populations. Factors that predispose the organism to autoimmunity and/or allergic responses are not well characterized in humans. WHO (1991) concluded, based on animal studies, that the most sensitive adverse effect for inorganic mercury risk assessments is the formation of mercury-induced autoimmune glomerulonephritis. Understanding dose-response among subpopulations that are particularly sensitive to the immunotoxic effects of mercury is limited and it is not scientifically possible to set a level of exposure below which mercury-related symptoms will not occur. This observation raises research questions, including the following: What is the magnitude of the risk of autoimmune disease associated with exposure to inorganic mercury? What is the dose-response relationships? Are there sensitive populations, and is the developing immune system particularly vulnerable? How can experimental animal research and epidemiology studies be linked to improve the risk assessment process?

Improved understanding of the effects on cardiovascular function as a result of methylmercury exposure. There are some human data linking cardiovascular effects with exposure to elemental, inorganic, and organic forms of

mercury. In addition, there are two recently published studies that show an association between low-level methylmercury exposure and cardiovascular effects. In a study of Faroese children, diastolic and systolic blood pressures increased as the cord-blood mercury increased from 1 to 10 µg/L. I a study in Finland, men with hair mercury 2 ppm or higher, had a 2.0 times greater risk of acute myocardial infarction than the rest of the study population. Relatively subtle effects of methylmercury on cardiovascular indices may have public health implications. As demonstrated with lead exposure, even a small elevation in blood pressure results in an increase in both myocardial infarctions and deaths.

Biological monitoring for model development and improvement. There is a need to conduct biological monitoring of sensitive populations who consume large amounts of fish and seafood in order to determine methylmercury intakes from diet and monitor blood- and hair-mercury concentrations. These sub-populations should include young children as well as adults and ethnically diverse groups. The populations should include groups who ingest fish and marine mammals that are highly contaminated with methylmercury (*e.g.,* people consuming fish from contaminated freshwater lakes) and those who consume high levels of fish and marine mammals with typical (*e.g.,* 0.05 - 0.2 ppm) mercury concentrations. The biomonitoring data need to be collected in a way that permits the development of toxicokinetic models that describe the tissue distributions of the comparable doses of mercury and methylmercury that are ingested in diverse temporal patterns.

Development of toxicokinetic data on methylmercury tissue distribution. Research is needed to establish the kinetic patterns (e.g., tissue distribution, ratios of hair mercury to blood mercury to dietary intakes) of mercury distribution following ingestion by children of methylmercury from dietary sources. Such data form the basis of a toxicokinetic model for predicting changes in risk from changes in the amount of exposures to mercury and methylmercury.

5.9.1.4 Research Results

Results from this research will be factored into refined mercury human health risk assessments that will be used to support future policy decisions on safe mercury levels for susceptible populations. Using these refined risk assessments, the Office of Air and Radiation (OAR) and the Office of Water (OW) will be able to make improved regulatory decisions on mercury atmospheric emissions and provide more informed guidance on methylmercury in water bodies. This work will also assist States and Regions in deciding when fish consumption advisories are needed to protect public health from methylmercury.

5.9.1.5 Measures of Success

Researchers hope to advance the following:

- A sufficient understanding of the biokinetics of mercury and methylmercury in young children to permit interpretation of monitoring and modeling data from various ongoing research projects.
- An improved determination as to whether young children or maternal-fetal pairs are the population at greatest risk from methylmercury exposures.
- An improved determination concerning the relative sensitivity of neurotoxic, immunotoxic, and cardiovascular effects.
- Improved understanding of the mechanism of delayed neurotoxicity, and the body burden at which it occurs
- Measurable improvement in the scientific understanding of the variability in fish/methylmercury consumption among the most highly exposed sub-populations in the United States.
- Measurable improvement in the scientific understanding of the relationship between risk from fish and marine mammal consumption during childhood, and risk from fish and marine mammal consumption during fetal development.

5.9.1.6 Preliminary Performance Goals

GPRA performance goals have been identified for the human health effects and exposure research area based on the above Measures of Success; they are preliminary in nature and will be revised and adjusted as part of the implementation of the *Mercury Research Strategy*. ORD anticipates that completion of the *MRS* will take approximately five to ten years depending on funding levels and any adjustments for changing Program Office and Regional needs. A preliminary set of performance goals is offered below. The performance goals are:

- By 2005, identify the impacts from aggregate exposures and synergistic relationships among other commonly occurring environmental pollutants (e.g., dioxin, PCBs, dibenzofurans).
- By 2007, establish the relationships between low-dose exposure to methylmercury throughout the life span of humans and animals and carcinogenic, reproductive, neurological, and immunological effects.
- By 2009, establish the relationships among delayed neurological effects after years of methylmercury exposure, especially any effects as a result of low-dose prenatal exposures.
- By 2009, provide toxicokinetic models that describe the underlying toxicity of methylmercury to a variety of susceptible populations.

5.10 RISK COMMUNICATION

5.10.1 Key Scientific Question

What are the most effective means for informing susceptible populations of the health risks posed by mercury and methylmercury contamination of fish and seafood?

5.10.1.1 Background

EPA anticipates a long lag time in controlling environmental levels of methylmercury, a known neurotoxin. If all current anthropogenic emissions of mercury ceased immediately, humans would still be exposed to elevated methylmercury levels in fish and seafood for a number of years. This lag from control of anthropogenic sources to measurable reductions in environmental mercury contaminant levels is the result of global mercury cycling from natural and re-emitted sources. Regardless of the time it takes to see meaningful reductions of mercury in both fish and humans as emissions are reduced, EPA must clearly communicate the facts on mercury and methylmercury to those exposed. In particular, the Agency needs to effectively communicate the nature and extent of risks to human health posed by methylmercury fish and seafood contamination to members of susceptible populations.

Susceptible populations include people consuming above-average amounts of fish (*e.g.,* more than approximately 10 grams per day) on a regular basis. Higher than average consumption of fish and other seafood is found among people of Asian and Native American ethnicity, recreational anglers and their families. People who are subsistence fishers may be a particularly important population with respect to methylmercury exposures. The extent of exposure depends on the amount of fish consumed and on the methylmercury concentrations in the fish. Methylmercury adversely affects the developing nervous system at lower exposure than it affects adult neurological functioning. Consequently, women of childbearing age, maternal/fetal pairs, nursing mother/infant pairs, and young children are all included as susceptible populations. Because brain development continues during early childhood, young children, along with pregnant/nursing mothers, need to be aware of the health hazards posed by ingestion of an excessive amount of methylmercury from fish and seafood.

5.10.1.2 Program Relevance

The Agency works with various communities and exposed populations to inform them of the dangers they face from environmental contaminants. This philosophy of community involvement forms the basis for fish advisory programs supported by EPA and run by state and local organizations and governments. As noted earlier, EPA anticipates a long lag time in reducing environmental levels of methylmercury once anthropogenic mercury sources are controlled. Better-informed populations and individuals need information delivered in a way that helps them understand the magnitude of methylmercury exposures produced by particular patterns of fish consumption. An adequate research base is needed to effectively inform populations at risk of their potential exposures. Exposure data and the effectiveness of its delivery provides useful dose-response information to assist in making informed choices on fish and seafood consumption. There are several research needs related to risk communication. The amount of mercury and methylmercury in fish varies markedly with geographic location, which reflects the impact of local factors. For example, similar lakes within a few miles of each other may have decidedly different methylmercury bioaccumulation patterns in fish. Consequently there is a need for monitoring data on mercury and methylmercury levels in water bodies and in fish. These data provide specific information to individuals and groups consuming fish from these water bodies.

5.10.1.3 Prioritized Research Needs

- *Synchronization of fish consumption advisory messages for methylmercury.*
- *Improved understanding of exposure patterns in targeting of risk messages.*
- *Increased use of risk information in making decisions about methylmercury exposures.*

Synchronization of fish consumption advisory messages for methylmercury. Research on how individual states have arrived at their fish advisory decisions is needed. Current state advisories on fish consumption use a variety of health-based approaches in setting advisory levels. Although all of these values are based on methylmercury concentrations in fish, some use EPA's RfD, some use ATSDR's 1999 revision of the Minimal Risk Level (MRL), and some use FDA's Action Level. In view of the National Academy of Science support for EPA's RfD as the appropriate level for protection of public health, the development of a synchronized strategy to communicate risk is preferred to the current approach.

Improved understanding of exposure patterns in targeting of risk messages. Data on the distribution patterns of fish consumption is needed. The Agency is concerned about risks resulting from exposure to methylmercury from multiple sources. For example, certain populations may consume both locally caught and commercial fish. Both of these sources of fish may be contaminated with methylmercury resulting in additive exposures. In the past, risk communications from the Agency have focused almost exclusively on locally caught fish. By contrast, several states include commercial fish in their advisories. A

challenge for the Agency is to develop approaches to communicate risk from methylmercury in both commercially available and locally caught fish.

In developing risk communication materials, an analysis of data on how much mercury populations are exposed to from fish is needed to provide a better basis for alerting individuals and groups about their level of risk from methylmercury exposures. A recommendation for obtaining data on human exposure to methylmercury from fish is also made under the human health effects and exposure key scientific question. Specifically, data are needed to describe the distribution of mercury concentrations in locally caught and commercially available fish are required in order to accurately inform susceptible populations of their total exposure to methylmercury. Data needs include the distribution of patterns of fish consumption.

Increased use of risk information in making decisions about methylmercury exposures. An additional risk communication research need is understanding how people use risk information to make informed decisions regarding methylmercury exposures. This is particularly complex because the populations at greatest risk (*e.g.,* infants, young children) have not reached a level of cognitive development to permit such choices. The individuals or groups to reach are parents or other responsible people. This area of risk communication has rarely been explored and represents a major opportunity for EPA to play an effective role in its development. Populations at highest risk of methylmercury exposure from eating fish include some immigrant groups (*e.g.,* persons of Asian and Pacific Island ethnicity), specific Native American tribes, individuals who may be pursuing a "healthy diet" (*e.g.* a diet high in polyunsaturated fatty acids to reduce the risk of cardiovascular disease), as well as individuals who simply prefer not to consume red meat. Because the motivations of these various individuals and groups differ markedly, research on how to communicate risk is likely to vary greatly also. Research is needed on how to successfully communicate the risk of methylmercury to such divergent populations, groups and individuals. Such messages are complex for two additional reasons: (a) the health benefits of fish consumption, and (b) differences in mercury concentrations in fish depending on species, size, and geographic location.

5.10.1.4 Research Results

Results from this research will contribute to a risk communication program for methylmercury in several ways. There is a need to synchronize fish consumption advisory messages for the numerous states in which they are issued. An understanding of how states have chosen to make fish advisory decisions would be an essential element of any synchronization effort. An improved understanding of exposure patterns (*e.g.,* amount of fish consumed, types of fish consumed, frequency of consumption) will assist in targeting populations and the messages those populations receive regarding methylmercury exposure based on fish consumption. This work will assist Program Offices and Regions, state and local governments, and other public and private groups in providing more effective risk information on methylmercury exposures.

5.10.1.5 Measures of Success

Researchers hope to advance the following:

- Mapped distribution of mercury levels in fish found in all waterways of the United States.
- Identification of the risk communication styles utilized by women of childbearing age from ethnically-diverse populations.
- Identification of the populations (based on ethnic, racial, economic, tribal groups) of greatest concern with regard to ingestion of methylmercury from fish and seafood.
- Development of fish advisories of proven effectiveness that reach 90 percent of the at-risk population.
- Development of a consistent state advisory system based on the use of EPA's RfD which was judged by the National Academy of Sciences Committee to be the scientifically justifiable value for protection of public health.
- Development, with appropriate professional groups (*e.g.,* obstetricians, state medical officers, state fishery experts), of risk messages aimed at informing particular sub-populations.
- Focus group testing of risk messages to multi-cultural, multi-ethnic groups of women of child-bearing age to determine how to promote changes in fish consumption behavior.
- Utilization of multimedia sources of risk information (*e.g.*, web-based and other electronic media).

5.10.1.6 Preliminary Performance Goals

GPRA performance goals have been identified for the risk communication research area based on the above Measures of Success; they are preliminary in nature and will be revised and adjusted as part of the implementation of the *Mercury Research Strategy*. ORD anticipates that completion of the *MRS* will take approximately five to ten years depending on funding levels and any adjustments for changing Program Office and Regional needs. A preliminary set of performance goals is offered below for the risk communication research area. The performance goals are:

- By 2005, describe risk communication styles for those populations with the greatest exposure to methylmercury in fish and seafood.
- By 2007, determine the best methods of communicating risk from methylmercury in fish and risk management

opportunities for mercury reduction, both domestically and internationally.

1. International data on mercury use and releases are difficult to obtain. For non-combustion sources, a few countries (*e.g.*, Sweden) appear to be more advanced in reducing mercury use. Mercury use appears to be growing in many other countries, especially developing nations, where their releases are often poorly controlled. International sources may have more significant releases to the global mercury pool than those from the United States. The Agency is developing an international mercury strategy into which the results of research described in this section will feed. (Unless otherwise stated, all discussions in this section deal with the use and release of mercury in the United States.)

6.0 ISSUES BEYOND THE MERCURY RESEARCH STRATEGY

The *Mercury Research Strategy* describes ORD's research program to reduce the scientific uncertainties related to mercury and methylmercury risks. There are, however, additional issues that the *MRS* Writing Team believes are important but which lie outside the scope of the mercury research program. These include science activities not considered "research," but that inform research efforts. Another issue is the development and implementation of mechanisms that encourage future research partnering external to EPA.

6.1 SCIENCE ACTIVITIES THAT GO BEYOND RESEARCH

In the process of preparing the *MRS*, ORD identified three science activities that provide data and information important to the success of the Agency's mercury risk assessment and risk management efforts. These three activities are: (1) improving mercury emission inventories and collecting source emission data, (2) monitoring mercury in various media, and (3) understanding the international implications of mercury. Each is described below in greater detail, as is ORD's suggested approach for addressing them. Furthermore, the information developed from these three activities will help EPA attain the goals identified in the Agency's *Mercury Action Plan* and in other documents including: *A Multimedia Strategy for Priority Persistent, Bioaccumulative and Toxic (PBT) Pollutants*; *Deposition of Air Pollutants to the Great Waters: Third Report to Congress*; and *North American Regional Action Plan for Mercury - Phase II* (Federal Register, 1998; EPA, 2000a; CEC, 2000). Resulting data and insights will allow for periodic adjustments in implementation of the *Mercury Research Strategy*.

6.1.1 Improving Mercury Emissions Inventories and Collecting Source Emissions Data

EPA collects data on mercury sources and releases from the National Toxics Inventory (NTI); it is the most comprehensive mercury emissions inventory of U.S. anthropogenic sources available. Nevertheless, EPA's current understanding of mercury sources and their characterization needs enhancement. The NTI provides a compilation of emissions estimates for all listed hazardous air pollutants (HAPs) for point, area, and mobile sources. It incorporates information from the Toxics Release Inventory (TRI), which includes manufacturers' submitted estimates of facility emissions to EPA, state and local inventory data, and data from other special studies. With respect to available information, EPA's TRI does not include mercury estimates for U.S. anthropogenic sources; that will change for the 1999 reporting period (due in 2001). In the 1999 reporting year, mercury releases of 10 pounds or more must be reported (Federal Register, 2000). The 1999 TRI inventory will not contain information on mercury species. EPA is gathering mercury emission data, for coal-fired utilities as part of the Utilities Information Collection Request (ICR). The ICR does contain some speciated mercury data.

EPA needs to better quantify, characterize, and inventory mercury released from domestic, non-combustion anthropogenic sources, diffuse area sources, and natural sources. There is also a need for data showing trends in mercury releases from these sources, both domestically and internationally. These trends will demonstrate the effectiveness of mercury source reduction efforts. An inventory of national and international speciated mercury is essential to effectively model mercury releases from human activities and predict deposition and concentrations in the environment. ORD is exploring how best to address these needs with the Program Offices (particularly OAR, OW, OPPTS, and OIA). ORD has adjusted the *MRS* to focus more effort on anthropogenic releases of mercury from non-combustion sources. This will be done as part of the risk management for non-combustion sources research area.

6.1.2 Monitoring Mercury in Various Media

While no comprehensive, national monitoring network for mercury has been developed, an increasing number of mercury monitoring activities are underway. EPA and others have developed ambient air and deposition monitoring networks that address mercury (with other pollutants) on local or regional scales (EPA, 2000a; CEC, 2000). There is, however, a need for statistically-representative monitoring data that provide a baseline against which progress in mercury risk management can be measured. ORD recognizes the need to develop and implement such a network, including the tracking of indicators to demonstrate changes in mercury concentrations in the environment. In particular, data are needed on both fish tissue (the primary route of human and wildlife exposure) and susceptible populations. This biomonitoring would track mercury concentration trends in both humans and fish.

EPA is preparing an Action Plan for mercury, one of the twelve priority pollutants identified in the *Draft Persistent Bioaccumulative Toxics (PBT) Strategy* (Federal Register, 1998). This action plan recommends the development of a comprehensive and focused *National Mercury Monitoring Strategy* (which may be expanded to include other PBTs). The monitoring strategy is intended to harmonize

monitoring programs underway by federal and state agencies and to achieve efficient and comprehensive mercury analyses on a national scale. It will include atmospheric, water, soil/sediment, and tissue monitoring. A weighted sampling design is envisioned for long-term monitoring on a broad scale. More intense monitoring, including key interacting variables, will be proposed for a set of sentinel sites. While ORD will participate in the design and implementation of this *National Mercury Monitoring Strategy* and consult in the network's operation, it does not intend to operate the network. The operation of a monitoring network of this magnitude lies outside of ORD's mission, and must be a coordinated effort among the Program and Regional Offices, states, and other organizations.

6.1.3 Understanding the International Implications of Mercury

It is increasingly clear that the atmospheric, transboundary nature of mercury needs to be considered as part of any mercury risk management effort in the United States. Based on the *Mercury Study Report to Congress* (EPA, 1997a), the estimated emissions of mercury from the U. S. are relatively small when compared to releases worldwide. Mercury, like other hazardous air pollutants, is both a global and national issue. A better understanding of how mercury cycles through the global environment is essential to achieve the effective management of mercury risks. The most pressing questions that remain regarding mercury revolve around mercury transport, transformation, and fate from emission release point through bioaccumulation in fish. In addition, a better understanding is needed of mercury chemistry, thermodynamics, and kinetics, both in the atmosphere and aquatic ecosystems.

On the global front, EPA's Office of International Activities and Office of Air and Radiation are contemplating the development of an *International Mercury Strategy*. The strategy will set the framework and rationale to guide the Agency's efforts, in concert with other organizations and the international community. The international strategy will focus on collecting scientific data, building international partnerships, and influencing risk management decisions, all with the goal of preventing or reducing mercury risks worldwide. ORD plans to contribute to the development and implementation of this strategy.

6.2 FOSTERING FUTURE RESEARCH PARTNERSHIPS

Engaging and partnering with a variety of stakeholders will enhance ORD's mercury research program. ORD wants to strengthen research links to the regulated community, in order to gain their participation and sponsorship of mutually beneficial mercury research. It is seeking links to states, communities, and tribes, in order to gather insights from decision makers at various community levels on their mercury research needs. The *MRS* Writing Team has worked closely with EPA's Program Offices and Regions to understand their research needs and involve them in the development of the *Mercury Research Strategy*.

ORD is now engaging other organizations in order to exchange information on mercury research and development activities and to advance its mercury research program. One area deserving attention involves Native Americans, particularly those individuals and tribes who rely on fish for a significant part of their diets. ORD will work through the newly-formed Tribal Science Council and as appropriate, the Arctic Monitoring and Assessment Program, to engage Native Americans on mercury issues. In both cases, these engagements will inform ORD's mercury research program, and in particular, the risk communication research area. Involvement with the international community will be pursued under the auspices of the *International Mercury Strategy* as it evolves in the coming months and years.

Examples of existing partnerships and potential opportunities for partnering with federal, private, public, and academic organizations are described in Chapter 4.0. For example, ORD has partnered with the U. S. Geological Survey (USGS) in establishing a USGS/EPA Mercury Roundtable. The Roundtable sponsors regularly scheduled meetings for the staffs of the two organizations to discuss science and its role in affecting policy related to mercury. Both organizations anticipate that this forum will evolve into a more broadly-based Federal Mercury Roundtable in the coming months. One outcome of this federal agency engagement is envisioned to be a biennial conference on federal agency mercury and methylmercury research. This conference will bring together not only EPA and USGS researchers, but others in the public and private sectors conducting pertinent research on mercury.

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APPENDIX A

SUMMARY OF STAR GRANTS PROGRAM AWARDS
Mercury: Transport and Fate through a Watershed

Appendix A contains a summary of grants awarded as part of ORD's Science to Achieve Results (STAR) Grants Program on mercury transport and fate through a watershed. In 1998, ORD issued a Request for Applications (RFA) inviting interested parties to submit research ideas that advance the fundamental understanding of chemical and physical transformations and movement of mercury in the environment (EPA 1998e). The awards summarized below were made in September 1999 and generally have a lifetime of three years. Specifically, the grants focus on the aquatic and terrestrial transport, transformation, and fate of mercury. The total funding for the research program over its three-year life is approximately $6.2 M. Each summary includes a description of the research being conducted, the institution conducting the research, and the principal investigator(s) leading the efforts. The summaries were prepared by the Principal Investigators as part of their proposal submissions. Additional information on the STAR Grants Program can be obtained by contacting EPA's National Center for Environmental Research (NCER) at http://www.es.epa.gov/ncerqa/.

Title: Methylmercury Sources to Lakes and Forested Watersheds: Has Enhanced Methylation Increased Mercury in Fish Relative to Atmosphere Deposition?

Institution: University of Minnesota/Minnesota Pollution Control Agency

Principal Investigator: Edward B. Swain

Summary:

The study will investigate enhanced methylmercury loads that results in elevated mercury concentrations in fish. The objectives of the study are to: (1) establish the relative importance of atmospheric, in-lake, and wetland sources of methylmercury to a lake in a forested watershed containing three types of wetlands; (2) determine the net retention and source strength of different wetland types; (3) conduct mesocosm (wetland and lake) and whole wetland experiments to elucidate methylation enhancing processes; and (4) add a hydrologically-based wetland GIS module to the Mercury Cycling Model (MCM) to apply finding to a larger set of lakes where GIS and mercury data have been collected.

The research will be conducted by the University of Minnesota and the Minnesota Pollution Control Agency and will focus on the sediments and fish in lakes within the State of Minnesota. Researchers hope to apply the study's findings to other regions of the country. The study will use a three-tiered approach involving microspace experiments, lake/wetland studies, and evaluation of the new understanding through modeling. Through this study, researchers will improve the understanding of the sources of methylmercury in fish and explain the observed differences in fish mercury levels in Minnesota and elsewhere.

Title: Response to Methylmercury Production and Accumulation to Changes in Hg Loading: A Whole-ecosystem Mercury Loading Study

Institution: The Academy of Natural Sciences Estuaries Research Center, The University of Maryland, Chesapeake Biological Laboratory, Canada Department of Fisheries and Oceans, Freshwater Institute.

Principal Investigator: Cynthia C. Gilmore

Summary:

The study attempts to understand the mercury cycle by studying methylmercury production as part of a whole-ecosystem mercury loading experiment. Researchers will attempt to answer the question of "How much does methylmercury in an ecosystem change in response to a change in mercury loading?" The study will measure the net accumulation of methylmercury, instantaneous methylmercury production and degradation rates, and the key biogeochemical parameters in each of these locations that affect mercury bioavailability and methylation.

The research will be conducted by several institutions (see above). United States and Canadian scientists will conduct the research at the Experimental Lakes Area (ELA) in northwestern Ontario. In addition, an experiment will also be conducted in the Florida Everglades for comparison of mercury loading. Researchers will use two approaches to study mercury loadings: (1) the stable mercury isotopes and (2) the manipulation of a whole watershed with mercury. The results will allow researchers to predict changes in methylmercury from changes in mercury loading over the range of mercury loadings that would result from regulatory action. The resulting data will also provide insights on regional and landscape variations that affect methylmercury production and accumulation in fish.

Title: Photo Induced Reduction of Mercury in Lakes, Wetlands, and Soils

Institution: University of Michigan, Oak Ridge National Laboratory

Principal Investigator: Jerome O. Nriagu

Summary:

The study will evaluate photosynthesis induced formation of mercury in a watershed. A comparison between the similarities and differences in pathways and rates of mercury formation in different segments of a watershed will be conducted. The study will measure the diurnal and seasonal variations in cross-gradient generation of mercury and total release of mercury from surface waters.

The experiments will be conducted in both laboratory and field conditions. The field study will take place at Saginaw Bay and Lake Huron. Researchers hope that the data will help explain the process of natural mercury release into the environment and the role of this process in reducing the amount of mercury loading in the Great Lakes.

Title: Chemical and Biological Control of Mercury Cycling in Upland, Wetland and Lake Ecosystems in the Northeastern U.S.

Institutions: Syracuse University, Cornell University, Smith College, Tetra Tech, Inc.

Principal Investigator: Charles T. Driscoll

Summary:

The study will attempt to clarify the chemical and biological processes that regulate mercury transport, fate, and bioavailability in the northeastern United States. The study will also attempt to develop and apply a simulation model to explain these processes. The research objectives are to: (1) quantify patterns of transport and transformations of mercury species in an upland northern hardwood forest through adjacent wetlands; (2) evaluate the processes and mechanisms controlling methylmercury concentrations and transport in pore-water and surface water in wetlands; (3) evaluate historical patterns of mercury dynamics in soft-water lakes; and (4) develop and apply a lake/watershed mercury cycling model to a lake/watershed ecosystem.

The project will examine the: (1) transport of mercury and interactions with organic matter and metals in upland soil, wetlands and surface waters; (2) rates and controls of methylation and demethylation of mercury in organic matter-rich wetland environments; and (3) factors which influence historical changes in the deposition of mercury to lake sediments. Field watershed measurements and controlled experiments will be employed to quantify mercury behavior in a typical glaciated landscape in the Adirondack Region of New York.

The result of this study will provide information to the EPA and agencies in the northeast concerned with the consequences of elevated atmospheric mercury deposition. The study will develop and calibrate a comprehensive watershed mercury cycling model to be used in assessing regional effects of atmospheric mercury deposition on watershed and lake ecosystems.

Title: Processes Controlling the Chemical/Isotopic Speciation and Distribution of Mercury from Contaminated Mine Sites

Institution: Stanford University, University of Nevada-Reno, U.S. Geological Survey

Principal Investigator: Gordon E. Brown, Jr.

Summary:

Researchers will attempt to understand the physical and chemical processes that control the speciation and distribution of mercury in mine wastes and its release from mine sites. The study will attempt to (1) determine the chemical and isotopic speciation of mercury in natural samples; (2) test the transport of mercury on colloidal particles in laboratory column experiments; (3) examine the sorption processes of mercury on mineral particles common in sediments downstream from mine sites, as well as the effects of common aqueous ligand sulfate and chloride on Hg sorption processes; and (4) monitor the atmospheric emissions of mercury from selected mine waste sites representing different weathering and climatic regimes. The objective is to correlate emission levels with the chemical speciation of mercury in the mine wastes. Researchers will conduct the experiments at selected mining waste sites in the western United States.

The chemical and isotopic forms of mercury associated with mining wastes will be determined using spectroscopic and isotopic methods. Laboratory column experiments will be conducted to examine the transport of mercury by colloids. Sorption experiments will be conducted to examine the sorption of mercury on mineral particles. To measure atmospheric emissions of mercury, micrometeorological and flux chamber methods will be used. The result of the study will allow researchers to better understand the process involved in speciation and distribution of mercury in mining waste. It will also allow scientists to better characterize the risk associated with mercury in mine wastes for local and regional ecosystems.

Title: Microbiological and Physicochemical Aspects of Mercury Cycling in the Coastal/ Estuaries Waters of Long Island Sound and Its River-Seawater Mixing Zones.

Institution: Department of Marine Sciences, University of Connecticut

Principal Investigator: William F. Fitzgerald

Summary:

This research is designed to better understand how mercury cycling in natural water plays a key role in controlling the overall aquatic biogeochemistry of mercury and the bioavailability of mercury species. The study is a three-year comprehensive examination of the physicochemical and microbiological marine program to investigate reactions and processes controlling mercury emissions, cycling, and bioavailability in Long Island Sound and its watershed/coastal water interface. The objective of the study is to understand the aquatic biogeochemistry of mercury and interactions between the terrestrial watersheds and near shore marine waters.

The program will take place at the estuaries and coastal waters in Long Island Sound. Scientists will use previous mercury mass balance studies and are proposing an experimental and theoretical design that will allow the results to be applicable to other regions. The experimental aspect of the study will be conducted largely in the field but also will involve laboratory experiments. The project increase**s** the understanding of the role and environmental impact of in-situ mercury production and emissions on the aquatic and atmospheric mercury cycle. Researchers also hope to evaluate the importance of the in-situ biological synthesis of methylmercury on the behavior and fate of this toxic species in Long Island Sound and other areas.

Title: Understanding the Role of Sulfur in the Production and Fate of Methylmercury in Watersheds

Institution: Chesapeake Biological Laboratory, University of Maryland, Academy of Natural Sciences Estuaries Research Center

Principal Investigator: Dr. Robert P. Mason and Dr. Cynthia Gilmore

Summary:

Researchers will investigate the influence of sulfide and other parameters, and the relative importance of microbial community structure and activity to net methylmercury production in natural sediments and soils. The objective of this project is to understand the role of sulfur in mercury methylation and methylmercury fate and transport in watersheds. The hypothesis is that the decreased methylation of mercury in high sulfide environments results from changes in mercury availability to the methylating organisms while low production in sulfate-limited systems is driven by limitation of microbial activity.

Laboratory and field experiments will be conducted. Bioavailability of mercury to methylating organisms will be determined using bacterial cultures and natural sediments and soils, combining laboratory, field and mesocosm experiments. Engineered microorganisms will also be used to test the hypothesis about factors controlling mercury uptake by methylating bacteria. The study results will provide information needed to understand the factors controlling the formation, degradation, fate and transport of methylmercury in watersheds. In addition, the results will provide new information regarding the relationship between atmospheric deposition of mercury to watersheds and mercury bioaccumulation in piscivorous fish.

Title: The Redox Cycle of Mercury In Natural Waters

Institution: Department of Geosciences, Princeton University

Principal Investigator: Francois M. M. Morel

Summary:
The study will provide a better understanding of the parameters that control the flux of elemental mercury from natural waters to the atmosphere. Researchers will conduct a series of iterative laboratory and field experiments focused on the principal chemical and biological redox mechanisms that transform mercury between its divalent and elemental forms. Researchers will model simple systems and build up to more complex models of natural waters. Lab experiments will create the mechanisms and the rates of the processes of interest and will provide methods and probes for the field experiments.

The field experiments will cover a number of sites and will attempt to establish the actual occurrences of the mechanisms in nature and provide kinetic data. The result of the project will allow for better understanding of how parameters affect the rate of mercury loss from bodies of water to the atmosphere. It will also help answer the question of why bodies of water with similar inputs of mercury end up having different mercury loadings.

Title: Watershed Influences on Transport, Fate and Bioavailability of Mercury in Lake Superior

Institution: Bureau of Integrated Science Services, Wisconsin Department of Natural Resources, University of Wisconsin-Madison, and Lake Superior State University

Principal Investigator: James P. Hurley

Summary:

This study will assess the importance of watersheds in controlling sources, transport, fate and bioavailability of mercury in a northern temperate lake system. The specific objectives of the study are to: (1) determine the speciation and bioavailability of mercury transported to Lake Superior by representative tributaries/watersheds; (2) determine the importance of watershed-specific characteristics (soil type, land use, surficial deposits) that control physical/chemical forms of mercury transported downstream; (3) identify key mechanisms controlling mercury bioavailability and speciation in near-shore zones relative to open lake regions; and, (4) provide process-level information to complement concurrent development of mercury fate and transport models of the Lake Superior ecosystem. The approach uses a combination of field and laboratory studies with modeling to assess the importance of watershed processes in controlling mercury fate and transport in Lake Superior. Anticipated results will provide information on the links between atmospheric mercury deposition and accumulation of mercury in biota within the Lake Superior Basin.