

3. FINDINGS OF THE MERCURY STUDY REPORT TO CONGRESS

Sources Contributing to Mercury in the Environment

In the CAA, Congress directed U.S. EPA to examine sources of mercury emissions, including electric utility steam generating units, municipal waste combustion units and other sources, including area sources. The U.S. EPA interpreted the phrase "... and other sources..." to mean that a comprehensive examination of mercury sources should be made and to the extent data were available, air emissions should be quantified. Volume II of this Report describes in some detail various source categories that emit mercury. In many cases, a particular source category is identified as having the potential to emit mercury, but data are not available to assign a quantitative estimate of emissions. The U.S. EPA's intent was to identify as many sources of mercury emissions to the air as possible and to quantify those emissions where possible.

The mercury emissions data that are available vary considerably in quantity and quality among different source types. Not surprisingly, the best available data are for source categories that U.S. EPA has examined in the past or is currently studying.

Sources of mercury emissions in the United States are ubiquitous. To characterize these emissions, the types are defined in the following way:

- *Natural mercury emissions* -- the mobilization or release of geologically bound mercury by natural processes, with mass transfer of mercury to the atmosphere;
- *Anthropogenic mercury emissions* -- the mobilization or release of geologically bound mercury by human activities, with mass transfer of mercury to the atmosphere; or
- *Re-emitted mercury* -- the mass transfer of mercury to the atmosphere by biologic and geologic processes drawing on a pool of mercury that was deposited to the earth's surface after initial mobilization by either anthropogenic or natural activities.

Contemporary anthropogenic emissions of mercury are only one component of the global mercury cycle. Releases from human activities today are adding to the mercury reservoirs that already exist in land, water, and air, both naturally and as a result of previous human activities. Given the present understanding of the global mercury cycle, the flux of mercury from the atmosphere to land or water at any one location is comprised of contributions from the following:

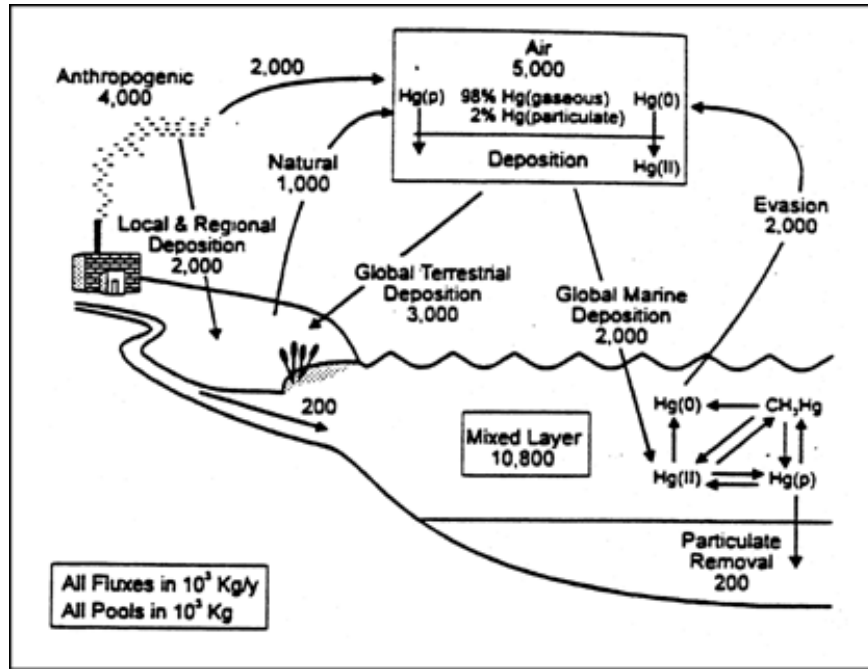
- The natural global cycle,
- The global cycle perturbed by human activities,
- Regional sources, and
- Local sources.

Local sources could also include direct water discharges in addition to air emissions. Past uses of mercury, such as fungicide application to crops are also a component of the present mercury burden in the environment.

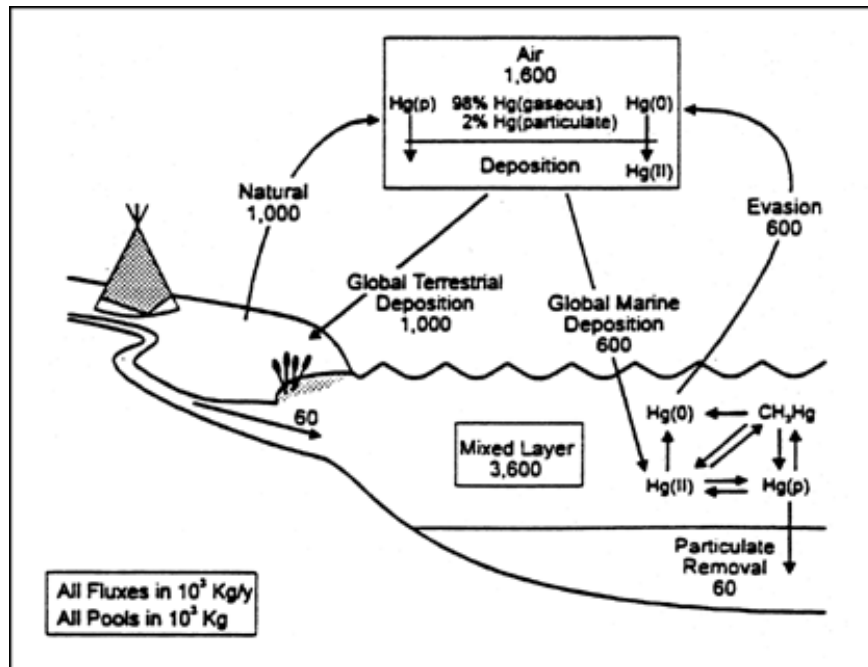
Understanding of the global mercury cycle (shown schematically in Figure 3-1) has improved significantly with continuing study of source emissions, mercury fluxes to the earth's surface, and the

Figure 3-1
 Comparison of Estimated Current and Pre-Industrial Mercury Budgets and Fluxes

Current Mercury Budgets and Fluxes



Pre-Industrial Mercury Budgets and Fluxes



Source: Adapted from Mason, R.P. Fitzgerald, W.F. and Morel, M.M. 1994. The Biogeochemical Cycling of Elemental Mercury: Anthropogenic Influences. *Geochem. Cosmochim. Acta*, 58(15):3191-3198.

magnitude of mercury reservoirs that have accumulated in soils, watersheds and ocean waters. Although considerable uncertainty still exists, it has become increasingly evident that anthropogenic emissions of mercury to the air rival or exceed natural inputs. Recent estimates place the annual amounts of mercury released into the air by human activities at between 50 and 75 percent of the total yearly input to the atmosphere from all sources. Recycling of mercury at the earth's surface, especially from the oceans, extends the influence and active lifetime of anthropogenic mercury releases.

A better understanding of the relative contribution of mercury from anthropogenic sources is also limited by substantial remaining uncertainties regarding the level of natural emissions as well as the amount and original source of mercury that is re-emitted to the atmosphere from soils, watersheds, and ocean waters. Recent estimates indicate that of the approximately 200,000 tons of mercury emitted to the atmosphere since 1890, about 95 percent resides in terrestrial soils, about 3 percent in the ocean surface waters, and 2 percent in the atmosphere. More study is needed before it is possible to accurately differentiate between natural emissions from these soils, watersheds and ocean water and from re-emissions of mercury which originated from anthropogenic sources. For instance, approximately one-third of total current global mercury emissions are thought to cycle from the oceans to the atmosphere and back again to the oceans, but a major fraction of the emissions from oceans consists of recycled anthropogenic mercury. According to the Expert Panel on Mercury Atmospheric Processes² 20 to 30 percent of the oceanic emission is from mercury originally mobilized by natural sources. Similarly, a potentially large fraction of terrestrial and vegetative emissions consists of recycled mercury from previously deposited anthropogenic and natural emissions.

Comparisons of contemporary (within the last 15-20 years) measurements and historical records indicate that the total global atmospheric mercury burden has increased since the beginning of the industrialized period by a factor of between two and five (see Figure 3-1). It is uncertain, however, whether overall atmospheric mercury levels are currently increasing, decreasing or remaining stable. Measurements over remote areas in the Atlantic Ocean show increasing levels up until 1990 and a decrease for the period 1990-1994. At some locations in the upper midwest of the U.S., measurements of deposition rates suggest decreased deposition at some locations. This decrease has been attributed to control of mercury emissions from local or regional sources. However, measurements at remote sites in northern Canada and Alaska show deposition rates that continue to increase. Since these remote sites are subject to global long-range sources rather than regional sources, these measurements may indicate that the global atmospheric burden of mercury is still increasing.

Although the estimated residence time of elemental mercury in the atmosphere is about 1 year, the equilibrium between the atmosphere and ocean waters results in a longer time period needed for overall change to take place in the size of the global reservoir. Therefore, by substantially increasing the size of the oceanic mercury pool, anthropogenic sources have introduced long term perturbations into the global mercury cycle. Fitzgerald and Mason³ estimate that if all anthropogenic emissions were ceased, it would take about 15 years for mercury reservoirs in the oceans and the atmosphere to return to pre-industrial conditions. The Science Advisory Board, in its review of this study concluded that it could take significantly longer. There is scientific agreement however, that the slow release of mercury from

²Expert Panel on Mercury Atmospheric Processes. September 1994. *Mercury Atmospheric Processes: A Synthesis Report*. Electric Power Research Institute. Report No. TR-104214.

³Fitzgerald, W. F., and R. P. Mason. 1996. The Global Mercury Cycle: Oceanic and Anthropogenic Aspects. Pp. 185-108 in Baeyens, W., R. Ebinghaus, and O. Vasiliev, eds., Global and Regional Mercury Cycles: Sources, Fluxes, and Mass Balances.

terrestrial sinks to freshwater and coastal waters will persist for a long time, probably decades, which effectively increases the length of time anthropogenic emissions would impact the environment. This is particularly significant given that the surface soils contain most of the pollution-derived mercury of the industrial period. As a result, it is uncertain at this time how long it would take after reductions in anthropogenic emissions for mercury levels in the global environment, including fish levels, to return to true background levels.

Because of the current scientific understanding of the environmental fate and transport of this pollutant, it is not possible to quantify the contribution of U.S. anthropogenic emissions relative to other sources of mercury, including natural sources and re-emissions from the global pool, on methylmercury levels in seafood and freshwater fish consumed by the U.S. population. Consequently, the U.S. EPA is unable to predict at this time how much, and over what time period, methylmercury concentrations in fish would decline as a result of actions to control U.S. anthropogenic emissions. This is an area of ongoing study.

Inventory Approach and Uncertainties

Given the considerable uncertainties regarding the levels of natural and re-emitted mercury emissions, the emissions inventory focused only on the nature and magnitude of mercury emissions from current anthropogenic sources. The U.S. EPA recognizes, however, that an assessment of the relative public health and environmental impact that can be attributed to current anthropogenic emissions is greatly complicated by both natural mercury emissions, previous emissions of mercury that have subsequently deposited and other sources such as water discharges and other previous uses (e.g., fungicide application). Further study is needed to determine the importance of natural and re-emitted mercury, and the contribution of water discharges relative to atmospheric deposition. Based on estimates of the total annual global input to the atmosphere from all sources (i.e., 5000 Mg from anthropogenic, natural, and oceanic emissions as illustrated by Figure 3-1), U.S. sources are estimated to contribute about 3 percent, based on 1995 emissions estimates as described below.

For most anthropogenic source categories, an emission factor-based approach was used to develop both facility-specific estimates for modeling purposes and nationwide emission estimates. This approach requires an emission factor, which is a ratio of the mass of mercury emitted to a measure of source activity. It also requires an estimate of the annual nationwide source activity level. Examples of measures of source activity include total heat input for fossil fuel combustion and total raw material used or product generated for industrial processes. Emission factors are generated from emission test data, from engineering analyses based on mass balance techniques, or from transfer of information from comparable emission sources. Emission factors reflect the "typical control" achieved by the air pollution control measures applied across the population of sources within a source category.

The emission factor-based approach does not generate exact emission estimates. Uncertainties are introduced in the estimation of emission factors, control efficiencies and the activity level measures. Ideally, emission factors are based on a substantial quantity of data from sources that represent the source category population. For trace pollutants like mercury, however, emission factors are frequently based on limited data that may not have been collected from representative sources. Changes in processes or emission measurement techniques over time may also result in biased emission factors. Emission control estimates are also generally based on limited data; as such, these estimates are imprecise and may be biased. Further uncertainty in the emission estimates is added by the sources of information used on source activity levels, which vary in reliability.

Once emitted to the environment, the fate and transport of mercury is greatly influenced by the chemical form of mercury. The data collected for the emissions inventory was all reported as total mercury with the exception of hazardous waste combustors for which there are site-specific speciated data. For medical waste incinerators and utility boilers there were limited speciated samples from a few facilities. In the exposure analysis described below, estimates were made of speciation profiles for modeling purposes. Speciated data derived from actual monitoring of sources are a critical research need. These data are needed to establish a clear causal link between mercury originating from anthropogenic sources and mercury concentration (projected or actual) in environmental media and/or biota.

To improve the emissions estimates, a variety of other research activities are also needed. These are listed in Chapter 5 of this Volume.

Anthropogenic Emissions Summary

Table 3-1 summarizes the estimated national mercury emission rates by source category. While these emission estimates for anthropogenic sources have limitations, they do provide insight into the relative magnitude of emissions from different groups of sources. All of these emissions estimates should be regarded as best point estimates given available data. Considering the data gaps and other uncertainties in the inventory, the external peer review panel that reviewed this work in January 1995 concluded that missing sources could contribute as much as 20 percent more mercury emissions to the U.S. total. This could affect the relative ranking of the smaller sources.

Of the estimated 144 Megagrams (Mg) (158 tons) of mercury emitted annually into the atmosphere by anthropogenic sources in the United States, approximately 87 percent is from combustion point sources, 10 percent is from manufacturing point sources, 2 percent is from area sources, and 1 percent is from miscellaneous sources. Four specific source categories account for approximately 80 percent of the total anthropogenic emissions--coal-fired utility boilers (33 percent), municipal waste combustion (19 percent), commercial/industrial boilers (18 percent), and medical waste incinerators (10 percent). It should be noted that the U.S. EPA has finalized mercury emission limits for municipal waste combustors and medical waste incinerators. When fully implemented, these emission limits will reduce mercury emissions from these sources by an additional 90 percent over 1995 levels.

All four of the most significant sources represent high temperature waste combustion or fossil fuel processes. For each of these operations, the mercury is present as a trace contaminant in the fuel or feedstock. Because of its relatively low boiling point, mercury is volatilized during high temperature operations and discharged to the atmosphere with the exhaust gas.

Trends in Mercury Emissions

It is difficult to predict with confidence the temporal trends in mercury emissions for the U.S., although there appears to be a trend toward decreasing total mercury emissions from 1990 to 1995. This is particularly true for the waste combustion sources where emissions have declined 50 percent from municipal waste combustors and 75 percent from medical waste incinerators since 1990 (see below). Also, as previously noted, there are a number of source categories where there is insufficient data to estimate current emissions let alone potential future emissions. Based on available information, however, a number of observations can be made regarding mercury emission trends from source categories where some information is available about past activities and projected future activities.

**Table 3-1
Best Point Estimates of National Mercury Emission Rates by Category**

Sources of mercury ^a	1994-1995 Mg/yr ^b	1994-1995 tons/yr ^b	% of Total Inventory ^b
Area sources	3.1	3.4	2.2
Lamp breakage	1.4	1.5	1.0
General laboratory use	1.0	1.1	0.7
Dental preparations	0.6	0.7	0.4
Landfills	<0.1	<0.1	0.0
Mobile sources	c	c	c
Paint use	c	c	c
Agricultural burning	c	c	c
Point Sources	140.9	155.7	97.8
Combustion sources	125.2	137.9	86.9
Utility boilers	47.2	52.0	32.8
Coal	(46.9) ^d	(51.6)	(32.6)
Oil	(0.2)	(0.2)	(0.1)
Natural gas	(<0.1)	(<0.1)	(0.0)
MWCs ^h	26.9	29.6	18.7
Commercial/industrial boilers	25.8	28.4	17.9
Coal	(18.8)	(20.7)	(13.1)
Oil	(7.0)	(7.7)	(4.9)
MWIs ^h	14.6	16.0	10.1
Hazardous waste combustors ^e	6.4	7.1	4.4
Residential boilers	3.3	3.6	2.3
Oil	(2.9)	(3.2)	(2.0)
Coal	(0.4)	(0.5)	(0.3)
SSIs	0.9	1.0	0.6
Wood-fired boilers ^f	0.2	0.2	0.1
Crematories	<0.1	<0.1	0.0
Manufacturing sources	14.4	15.8	10.0
Chlor-alkali	6.5	7.1	4.5
Portland cement ^e	4.4	4.8	3.1
Pulp and paper manufacturing	1.7	1.9	1.2
Instruments manufacturing	0.5	0.5	0.3
Secondary Hg production	0.4	0.4	0.3
Electrical apparatus	0.3	0.3	0.2
Carbon black	0.3	0.3	0.2
Lime manufacturing	0.1	0.1	0.1
Primary lead	0.1	0.1	0.1
Primary copper	<0.1	<0.1	0.0
Fluorescent lamp recycling	<0.1	<0.1	0.0
Batteries	<0.1	<0.1	0.0
Primary Hg production	c	c	c
Mercury compounds	c	c	c
Byproduct coke	c	c	c
Refineries	c	c	c
Miscellaneous sources	1.3	1.4	0.9
Geothermal power	1.3	1.4	0.9
Turf products	g	g	g
Pigments, oil, etc.	g	g	g
TOTAL	144	158	100

^a MWC = Municipal waste combustor; MWI = medical waste incinerator; SSI = sewage sludge incinerator.

^b Numbers do not add exactly because of rounding.

^c Insufficient information to estimate 1994-1995 emissions.

^d Parentheses denote subtotal within larger point source category.

^e For the purpose of this inventory, cement kilns that burn hazardous waste for fuel are counted as hazardous waste combustors.

^f Includes boilers only; does not include residential wood combustion (wood stoves).

^g Mercury has been phased out of use.

^h U.S. EPA has finalized emission guidelines for these source categories which will reduce mercury emissions by at least an additional 90 percent over 1995 levels.

Current emissions of mercury from manufacturing sources are generally low compared to combustion sources (with the exception of chlor-alkali plants using the mercury cell process and portland cement manufacturing plants). The emissions of mercury are more likely to occur when the product (e.g., lamps, thermostats) is broken or discarded. Therefore, in terms of emission trends, one would expect that if the future consumption of mercury remains consistent with the 1996 consumption rate, emissions from most manufacturing sources would remain about the same.

Secondary production of mercury (i.e., recovering mercury from waste products) has increased significantly over the past few years. While 372 Mg of mercury were used in industrial processes in 1996, 446 Mg were produced by secondary mercury producers and an additional 340 Mg were imported. This is a two-fold increase since 1991. The number of secondary mercury producers is expected to increase as more facilities open to recover mercury from fluorescent lamps and other mercury-containing products (e.g., thermostats). As a result there is potential for mercury emissions from this source category to increase.

The largest identified source of mercury emissions during 1994-1995 is fossil fuel combustion by utility boilers, particularly coal combustion. Future trends in mercury emissions from this source category are largely dependent on both the nation's future energy needs and the fuel chosen to meet those needs. Another factor is the nature of actions the utility industry may take in the future to meet other air quality requirements under the Clean Air Act (e.g., national ambient air quality standards for ozone and particulate matter).

Two other significant sources of mercury emissions currently are municipal waste combustors and medical waste incinerators. Emissions from these source categories have declined considerably since 1990 on account of plant closures (for medical waste incinerators) and reduction in the mercury content of the waste stream (municipal waste combustors). Mercury emissions from both of these source types will decline even further by the year 2000 due to regulatory action the U.S. EPA is taking under the statutory authority of section 129 of the CAA. The U.S. EPA has finalized rules for municipal waste combustors and medical waste incinerators that will, when fully implemented, reduce mercury emissions from both of these source categories by an additional 90 percent over 1995 levels. In addition to this federal action, a number of states (including Minnesota, Florida and New Jersey) have implemented mandatory recycling programs to reduce mercury-containing waste, and some states have regulations that impose emission limits that are lower than the federal regulation. These factors will reduce national mercury emissions from these source categories even further.

Trends in Mercury Use

Data on industrial demand for mercury show a general decline in domestic mercury use since demand peaked in 1964. Domestic demand fell by 74 percent between 1980 and 1993, and by more than 75 percent between 1988 and 1996. The rate of decline, however, has slowed since 1990. Further evidence of the declining need for mercury in the U.S. is provided by the general decline in imports since 1988 and the fact that exports have exceeded imports since at least 1989. Federal mercury sales steadily increased from 1988 to 1993, reaching a peak of 97 percent of the domestic demand. However, in July 1994, DLA suspended future sales of mercury from the Department of Defense stockpile until the environmental implications of these sales are addressed. In addition, in past years, DLA sold mercury accumulated and held by the Department of Energy, which is also considered excess to government needs. DLA suspended these mercury sales in July 1993 for an indefinite period in order to concentrate

on selling material from its own mercury stockpile. These suspensions caused federal sales to rapidly decrease to 18 percent of domestic demand in 1994 and to zero since 1995⁴.

For industrial or manufacturing sources that use mercury in products or processes, the overall consumption of mercury is generally declining. Industrial consumption of mercury has declined by about 75 percent between 1988 (1503 Mg) and 1996 (372 Mg). Much of this decline can be attributed to the elimination of mercury as a paint additive and the reduction of mercury in batteries. Use of mercury by other source categories remained about the same between 1988 and 1996.

In general, these data suggest that industrial manufacturers that use mercury are shifting away from mercury except for uses for which mercury is considered essential. This shift is believed to be largely the result of Federal bans on mercury additives in paint and pesticides; industry efforts to reduce mercury in batteries; increasing state regulation of mercury emissions sources and mercury in products; and state-mandated recycling programs. A number of Federal activities are also underway to investigate pollution prevention measures and control techniques for a number of sources categories (see Volume VIII of this Report to Congress).

Assessment Approach for Fate and Transport of Mercury

Study Design of the Fate and Transport Analysis

This analysis relied heavily on computer modeling to describe the environmental fate of emitted mercury because no monitoring data have been identified that conclusively demonstrate or refute a relationship between any of the individual anthropogenic sources in the emissions inventory and increased mercury concentrations in environmental media or biota. To determine if there is a connection between the above sources and increased environmental mercury concentrations, three different models were utilized. Volume III of this Report describes in detail the justification for choices of values for model parameters.

Given the scientific uncertainties associated with environmental mercury, U.S. EPA decided that it was most appropriate to examine the environmental fate of mercury at generalized, rather than specific, sites. A single air model which was capable of modeling both the local as well as regional fate of mercury was not identified. This resulted in the use of two air models: the Regional Lagrangian Model of Air Pollution (RELMAP), for assessing regional scale atmospheric transport, and the Industrial Source Code model (ISC3), for local scale analyses (i.e., within 50 km of a source). To examine the fate of mercury in terrestrial and aquatic environments, U.S. EPA modified an existing generalized watershed and water body fate model. The modified model is identified as IEM-2M. Each of the fate and transport models used in the analysis is summarized in Table 3-2.

⁴Plachy, Jozef, 1997. Mineral Industry Surveys: Mercury Annual Review 1996. Reston, VA. June 1997.

**Table 3-2
Models used in the Report to Congress**

Model	Function
RELMAP	Predict average annual atmospheric mercury concentrations as well as wet and dry deposition flux for 40 Km ² grids across the continental U.S. Model predictions were based on anthropogenic emissions from the sources described in Volume II, Inventory of Anthropogenic Mercury Emissions in the United States.
ISC3	Predict average annual atmospheric mercury concentrations as well as the wet and dry deposition fluxes that result from emissions within 50 Km of a single source.
IEM-2M	Predict environmental media concentrations and the exposures that result from atmospheric mercury concentrations and deposition.

In the first step of this risk assessment, RELMAP was used to simulate the regional-scale transport of anthropogenic mercury emissions over a one-year period. The predicted anthropogenic mercury emissions were added to a uniform elemental mercury background concentration of 1.6 ng/m³ which represented natural and recycled anthropogenic sources of mercury worldwide.

In the second step of the assessment, ISC3 was used to simulate the local-scale transport of anthropogenic mercury emissions. This approach was selected because environmental monitoring studies indicate that measured mercury levels in environmental media and biota may be elevated in areas around stationary industrial and combustion sources known to emit mercury. Rather than use actual facilities for this assessment, a set of model plants was defined to represent typical sources. The source categories evaluated were municipal waste combustors (MWCs), medical waste incinerators (MWIs), coal- and oil-fired utility boilers, and chlor-alkali plants. Two generalized sites where these plants could be located were developed to assess mercury emissions, deposition and subsequent transport through a watershed to a water body. These sites are referred to as the hypothetical western U.S. site and the hypothetical eastern U.S. site. The primary differences between the two hypothetical locations were the assumed erosion characteristics for the watershed and the amount of dilution flow from the water body. Both sites were assumed to have flat terrain for purposes of the atmospheric modeling. The background concentrations in all environmental compartments except for the atmosphere (e.g., soils and sediments) were also assumed to be higher in the eastern U.S. than in the west. The hypothetical eastern and western sites were “placed” at 2.5, 10, and 25 km from the sources (model plants). The ISC3 model predicted mercury air concentrations and deposition rates that resulted from individual model plants at the specified distances.

To estimate the total amount of atmospheric deposition at a site, the 50th or 90th percentile predictions of the RELMAP model for the western or eastern sites were added to the predictions of the local atmospheric model (ISC3) for the individual model plants. These combined model predictions of average atmospheric concentrations and annual-average deposition rates represent the total mercury one might see as a result of both emissions from a single source and impacts from other regional sources.

These estimates were used as inputs to the IEM-2M aquatic and terrestrial fate models at the hypothetical western and eastern U.S. sites.

In the third step of this risk assessment, IEM-2M was utilized to predict the different chemical species of mercury and their concentrations in watershed soils, the water column and sediments of the hypothetical lake, as well as in terrestrial and aquatic organisms. Soil concentrations are used along with vapor concentrations, deposition rates and biotransfer factors to estimate concentrations in various plants. These are used, in turn, along with other biotransfer factors to estimate concentrations in animals. Methylmercury (MHg) concentrations in fish are derived from dissolved MHg water concentrations using bioaccumulation factors (BAF). The BAF accounts for mercury accumulation in organisms that comprise the food web. The BAFs used in this analysis were calculated from existing field data.

A significant input to the IEM-2M model was the estimate of existing mercury concentrations in the environment. To determine existing background concentrations in soil, water, and sediments, U.S. EPA estimated current “background” atmospheric concentrations and deposition rates to the hypothetical western and eastern sites. Each site was then modeled using IEM-2M until equilibrium was achieved with the specified atmospheric background conditions. At both hypothetical sites, the fate of deposited mercury was examined in three different settings: rural (agricultural), lacustrine (around a water body), and urban. The resulting predictions of mercury concentrations in soil, water, and biota were then used to evaluate mercury exposures to humans and wildlife as described in Volumes IV and V of this Report.

Figure 3-2 illustrates the how the various fate models were integrated.

Long-Range Transport Analysis

The long range transport modeling predicts the regional and national deposition of mercury across the continental U.S. Details of several studies which demonstrate the long range transport of mercury are presented in Volume III. In this analysis, the long range transport of mercury was modeled using site-specific, anthropogenic emission source data (presented in Volume II of this Report) to generate average annual atmospheric mercury concentrations and deposition values across the continental U.S. The Regional Lagrangian Model of Air Pollution (RELMAP) was the model selected for this analysis.

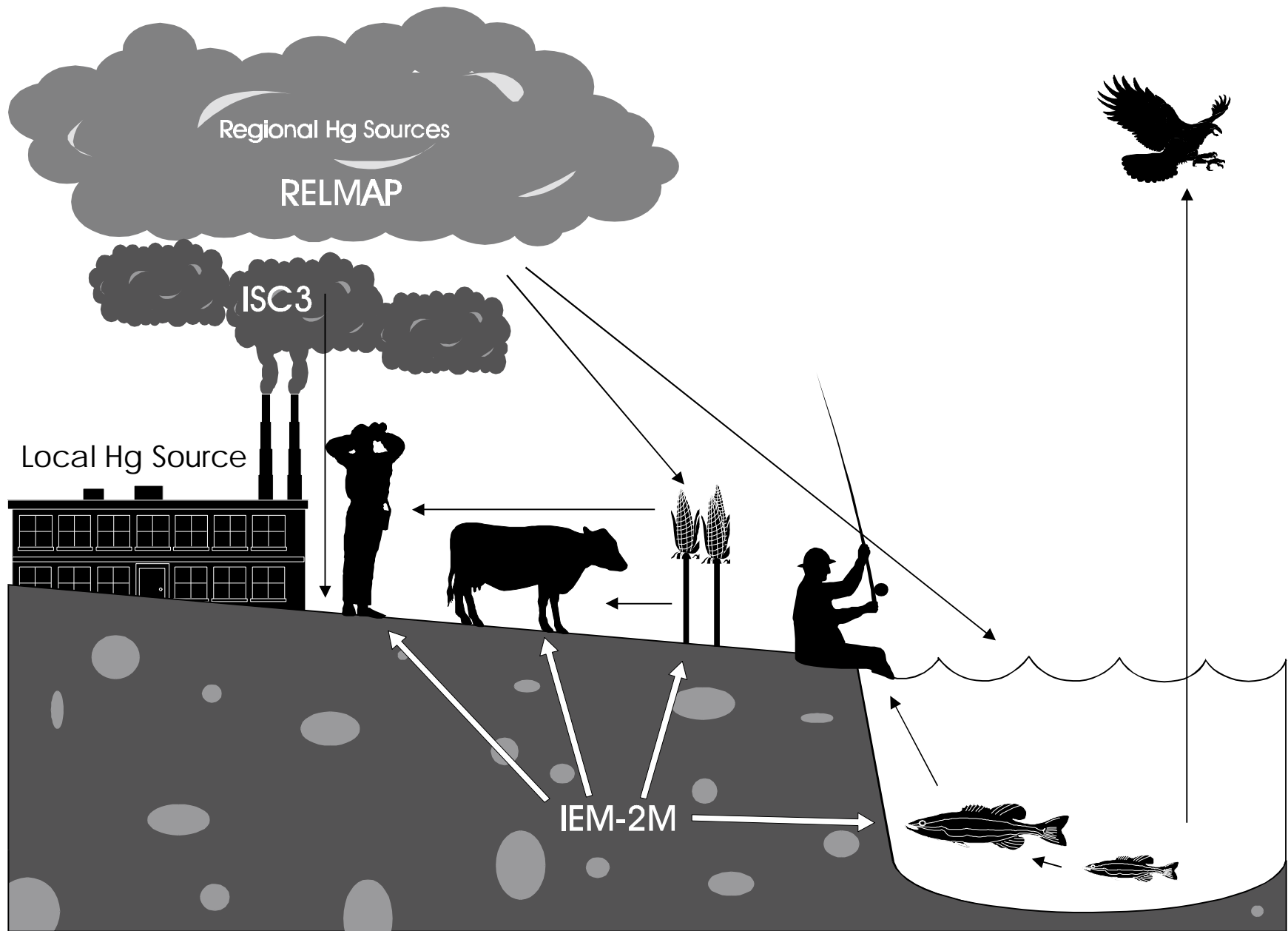
From the RELMAP analysis and a review of field measurement studies, it is concluded that mercury deposition appears to be ubiquitous across the continental U.S., and at, or above, detection limits when measured with current analytic methods. The southern Great Lakes and Ohio River Valley, the Northeast, and scattered areas in the South (particularly in the Miami and Tampa areas) are predicted to have the highest annual rate of deposition of total mercury (above the levels predicted at the 90th percentile). Figure 3-3 illustrates the pattern of mercury deposition across the U.S. This figure also illustrates the boundaries of the RELMAP modeling domain. Measured deposition data are limited, but are available for certain geographic regions. The data that are available corroborate the RELMAP modeling predictions for specific areas. These comparisons are discussed in detail in Volume III.

A wide range of mercury deposition rates is predicted across the continental U.S. The highest predicted rates (i.e., above 90th percentile) are about 20 times higher than the lowest predicted rates (i.e., below the 10th percentile).

The three principal factors that contribute to these modeled and observed deposition patterns are:

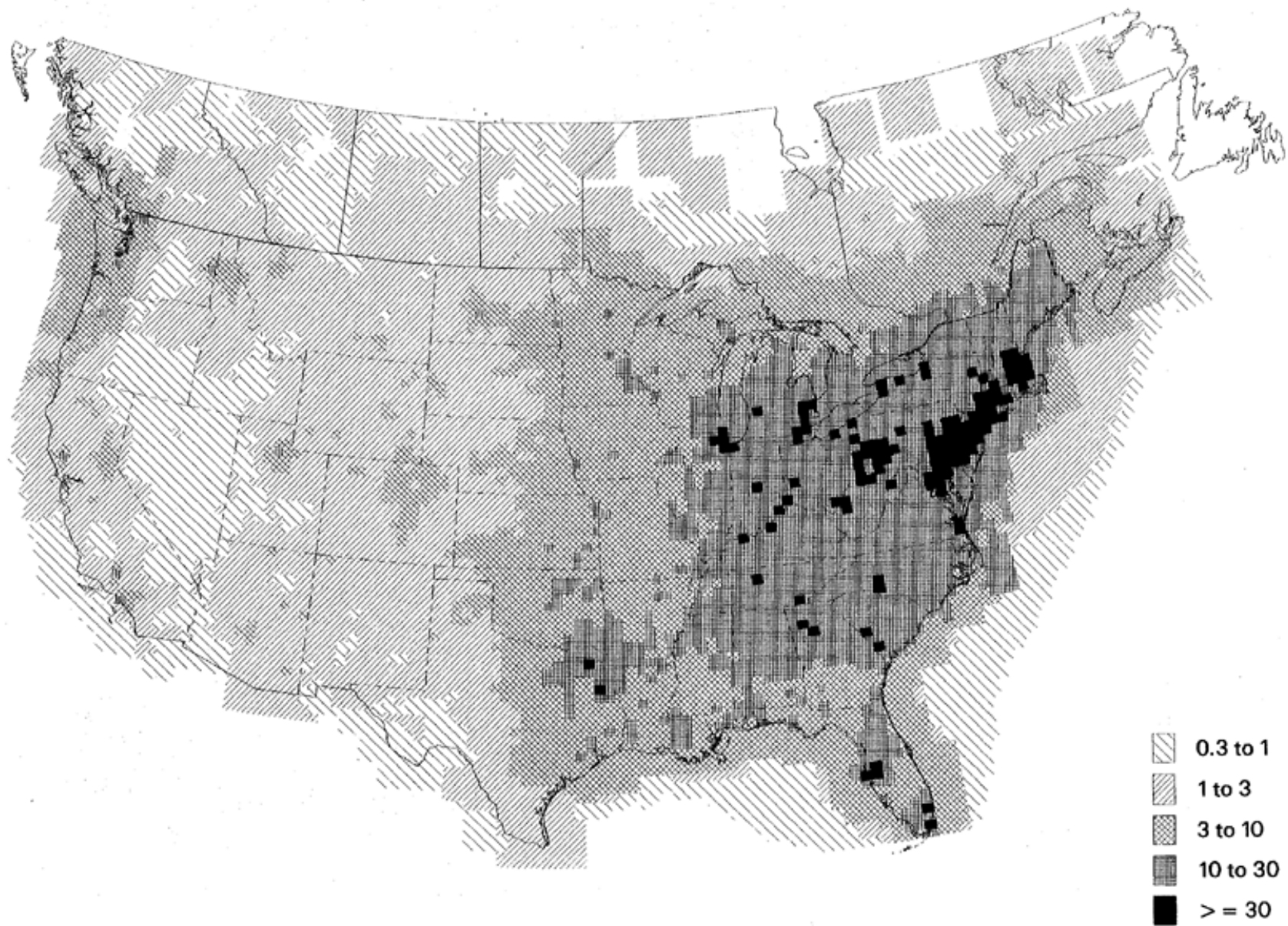
- the emission source locations;

Figure 3-2
Fate, Transport and Exposure Modeling Conducted in the Combined ISC3 and RELMAP Local Impact Analysis



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Figure 3-3
Total Simulated Wet + Dry Deposition of Mercury in All Forms
Units: $\mu\text{g}/\text{m}^2$



- the amount of divalent and particulate mercury emitted or formed in the atmosphere; and
- climate and meteorology.

A facility located in a humid climate is predicted to have a higher annual rate of mercury deposition than a facility located in an arid climate.

The critical variables within the model are:

- the estimated washout ratios of elemental and divalent mercury; and
- the annual amount of precipitation.

Precipitation is important because it removes various forms of mercury from the atmosphere and deposits them to the surface of the earth.

Mass Balances of Mercury within the Long-range Model Domain

The chemical form of emitted mercury is a critical factor in its fate, transport and toxicity in the environment. With the exception of hazardous waste incinerators, for which there are site-specific speciated data, mercury emissions are reported as total mercury in all forms. The form distributions, or speciation factors, define the estimated fraction of mercury emitted as elemental mercury (Hg^0), divalent mercury (Hg^{2+}), or mercury associated with particulates (Hg_p). These speciation factors were adopted from Peterson et al.⁵ with adjustments made to reflect the types of air pollution control equipment known to be installed at individual industrial plants. There is considerable uncertainty about the speciation factors for some industrial sources. A wide variety of alternate speciation scenarios have been investigated to measure the sensitivity of the RELMAP results to this uncertainty^{6,7}. The results show that the total simulated wet and dry deposition of mercury to the continental U. S. is strongly and positively correlated to the fraction of mercury emitted as Hg^{2+} and Hg_p for all major source types. The speciation factors used in the RELMAP modeling for this Report are discussed in Volume III.

The results of the RELMAP modeling using these assumed speciation factors are described below. The general mass balance of elemental mercury gas, divalent mercury gas, and particle-bound mercury from the RELMAP simulation results using specified speciation profiles are shown in Table 3-3. Using the meteorologic data from the year 1989, the mass balance shows a total of 141.8 metric tons of mercury emitted to the atmosphere from anthropogenic sources. (This simulated emission total differs from the national totals indicated in Volume II since the states of Alaska and Hawaii are not within the model domain.) The simulation indicates that 47.6 metric tons of anthropogenic mercury emissions are deposited within the model domain and 0.4 metric tons remain in the air within the model domain at the end of the simulation. The remainder, about 93.8 metric tons, is transported outside the model domain and probably diffuses into the global atmospheric reservoir.

⁵Petersen, G., Å. Iverfeldt and J. Munthe. (1995) Atmospheric mercury species over Central and Northern Europe. Model calculations and comparison with observations from the Nordic Air and Precipitation Network for 1987 and 1988. *Atmospheric Environment* 29:47-68.

⁶Bullock, Jr., O. R., W. G. Benjey and M. H. Keating. (1997) Modeling of regional scale atmospheric mercury transport and deposition using RELMAP. *Atmospheric Deposition of Contaminants to the Great Lakes and Coastal Waters: Joel E. Baker, Ed.* pp.323-347. SETAC Press, Pensacola, Florida.

⁷Bullock, Jr., O. R., K. A. Brehme and G. R. Mapp. (1997) Lagrangian modeling of mercury air emission, transport and deposition: An analysis of model sensitivity to emissions uncertainty. *Special Issue on Mercury as a Global Pollutant: Science of the Total Environment*, in press.

The simulation also indicates that 32.0 metric tons of mercury are deposited within the model domain from this global atmospheric reservoir, suggesting that about three times as much mercury is being added to the global reservoir from U.S. emissions as is being deposited from it. The total amount of mercury deposited in the model domain annually from U.S. anthropogenic emissions and from the global background concentration is estimated to be 79.6 metric tons, of which approximately three-fifths is emitted by anthropogenic sources in the lower 48 United States.

Of the total anthropogenic mercury mass deposited to the surface in the model domain, 77% is estimated by the RELMAP to come from Hg^{2+} emissions, 21% from Hg_p emissions and 2% from Hg^0 emissions. When the deposition of Hg^0 from the global background is considered in addition to anthropogenic sources in the lower 48 states, the species fractions of total deposition become 46% Hg^{2+} , 41% Hg^0 and 13% Hg_p . The vast majority of mercury already in the global atmosphere is in the form of Hg^0 and, in general, the anthropogenic Hg^0 emissions do not greatly elevate the Hg^0 air concentration over the global background value. Although Hg^0 is removed from the atmosphere very slowly, the global background reservoir is large and total deposition from it is significant. It should be noted that dry deposition of Hg^0 is thought to be significant only at very elevated concentrations and has not been included in the RELMAP simulations. Wet deposition is the only major pathway for removal of Hg^0 from the atmosphere. This removal pathway simulated by the RELMAP involves oxidation of mercury by ozone in an aqueous solution; thus, the Hg^0 that is extracted from the atmosphere by the modeled precipitation process would actually be deposited primarily in the form of Hg^{2+} .

Table 3-3
Modeled Mercury Mass Budget in Metric Tons for 1994-1995
Using the Specified Speciation Profiles and 1989 Meteorology

Source/Fate	Hg^{0a}	Hg^{2+b}	Hg_p^c	Total Mercury
Total U.S. anthropogenic emissions	63.5	52.3	26.0	141.8
Mass advected from model domain	62.3	15.5	16.0	93.8
Dry deposited anthropogenic emissions	0.0	22.9	0.5	23.4
Wet deposited anthropogenic emissions	0.9	13.8	9.5	24.2
Remaining in air at end of simulation	0.4	<0.1	<0.1	0.4
Total deposited anthropogenic emissions	0.9	36.8	10.0	47.6
Deposited from background Hg^0	32.0	0.0	0.0	32.0
Mercury deposited from all sources	32.9	36.8	10.0	79.6

(All figures rounded to the nearest tenth of a metric ton)

^a Hg^0 = Elemental Mercury

^b Hg^{2+} = Divalent Vapor-phase Mercury

^c Hg_p = Particle-Bound/Mercury

Of the 63.5 metric tons of anthropogenic Hg^0 emitted in the lower 48 states, only 0.9 tons (1.4%) is deposited within the model domain, while of the 52.3 metric tons of Hg^{2+} emitted, about 36.8 tons (70.4%) is deposited. Ninety-eight percent of the deposited anthropogenic mercury was emitted in the form of Hg^{2+} or Hg_p . Thus, a strong argument can be made that the combined Hg^{2+} and Hg_p component of anthropogenic mercury emissions can be used as an indicator of eventual deposition of those emissions to the lower 48 states and surrounding areas. The emission inventory and chemical/physical

speciations profiles indicate that of all combined Hg^{2+} and Hg_p emissions in 1994-1995, about 29% is from electric utility boilers, 25% is from municipal waste combustion, 18% is from medical waste incineration, 16% is from commercial and industrial boilers, and 12% is from all other modeled sources.

Limitations of the Long-Range Transport (RELMAP) Analysis

There are a number of uncertainties with the RELMAP analysis. These have to do to a large degree with the current state-of-the-science concerning atmospheric chemistry and speciation profiles of mercury emissions. Some of the most important limitations are listed below.

- Comprehensive emissions data for a number anthropogenic and natural sources are not available. This reflects the current developmental nature of emission speciation methods, resulting in few data on the various species of mercury and proportions of vapor and solid forms emitted. Both elemental and divalent mercury species as well as gaseous and particulate forms are known to be emitted from point and area sources.
- Atmospheric chemistry data are incomplete. Some atmospheric reactions of mercury, such as the oxidation of elemental mercury to divalent mercury in cloud water droplets have been reported. Other chemical reactions in the atmosphere that may reduce divalent species to elemental mercury have not been reported.
- There is inadequate information on the atmospheric processes that affect wet and dry deposition of mercury. Atmospheric particulate forms and divalent species of mercury are thought to wet and dry deposit more rapidly than elemental mercury; however, the relative rates of deposition are uncertain. There is no validated air pollution model that estimates wet and dry deposition of vapor-phase compounds close to the emission source. In addition, there is uncertainty regarding the revolatilization of deposited mercury.

Analysis of the Local Atmospheric Fate of Mercury

An analysis of the local atmospheric fate of mercury (within 50 km) released from anthropogenic emission sources was undertaken using the ISC-3 model to estimate the impacts of mercury from selected, individual source types. The ISC-3 model was slightly modified to correspond more closely to the chemical properties of atmospheric mercury. This analysis addressed atmospheric mercury emissions from MWCs, coal- and oil-fired utility boilers, MWIs, and chlor-alkali plants. A model plant approach was utilized to develop facilities which represent actual sources from these four categories. The model plants were situated in hypothetical locations intended to simulate a site in either the western or eastern U.S.

The ISC-3 model was used in conjunction with the results from the RELMAP regional scale modeling in order to estimate the air concentrations and deposition rates for each hypothetical facility in each site. Once emitted from a source, mercury may be deposited to the ground via two main processes: wet and dry deposition. Wet deposition refers to the mass transfer of dissolved gaseous or suspended particulate mercury species from the atmosphere to the earth's surface by precipitation, while dry deposition refers to such mass transfer in the absence of precipitation.

The model parameters exerting the most influence on the deposition rates are these:

- total mercury emission rate (grams/second);
- assumptions regarding speciation of the total mercury;
- vapor/particle phase partition estimate;
- stack height for the plant; and
- exit gas velocity.

Combined Results of Local and Regional Scale Analyses

The results of the local scale ISC-3 modeling and the regional scale RELMAP modeling were combined to predict air concentrations and deposition rates for each hypothetical facility in each site. The predicted air concentrations are typically dominated by the regional values, even for the watersheds relatively close to the facility. In general, the predicted average air concentrations are quite low. The only source class for which significantly elevated air concentrations are predicted is the chlor-alkali facility. This is due to a very low stack height coupled with a high assumed mercury emission rate. The low stack height results in predicted plumes that are close to the receptors considered, and so there is less dispersion of the plume compared to the other facilities.

In contrast to the predicted air concentrations, the annual deposition rates are *cumulative*; they represent the sum of any deposition that occurs during the year, and hence are not affected by long periods of little deposition. Further, the ISC3 model predicts that significant deposition events occur infrequently, and it is these relatively rare events that are responsible for the majority of the annual deposition rate. The percentage of mercury deposited within 50 km depends on two main factors: facility characteristics that influence effective stack height (stack height plus plume rise) and the fraction of mercury emissions that is divalent mercury. In most cases, the effective stack height affects only the air concentrations, and hence dry deposition.

For any site with appreciable precipitation, wet deposition can dominate the total deposition for receptors close to the source. Single wet deposition events can deposit 300 times more Hg than a high dry deposition event. These events are even rarer than significant dry deposition events because not only must the wind direction be within a few degrees of the receptor's direction, but precipitation must be occurring as well. The predicted dry deposition rates depend ultimately on the predicted air concentrations. For this reason, dry deposition accounts for most of the total deposition for the facility with the highest predicted air concentrations, the chlor-alkali plant.

In general, 7-45% of the total mercury emitted is predicted to deposit within 50 km at the eastern site in flat terrain, while 2-38% is predicted to deposit at the western site. (The ranges represent values from the different sources considered.) This implies that at least 55% of the total mercury emissions is transported more than 50 km from any of the sources considered, and is consistent with the RELMAP results that predict that mercury may be transported across considerable distances.

The differences between the results for the eastern and western sites are due primarily to the differences in the frequency and intensity of precipitation. At the eastern site, precipitation occurs about 12 % of the year, with about 5% of this precipitation of moderate intensity (0.11 to 0.30 in/hr). By comparison, at the western site, precipitation occurs about 3% of the year, with about 2% of the precipitation of moderate intensity.

Assessment of Watershed Fate

The atmospheric mercury concentrations and deposition rates estimated using the RELMAP and ISC3 were then used as inputs in the watershed model, IEM-2M, to derive calculations of mercury in watershed soils and surface waters. The soil and water concentrations, in turn, drive calculations of concentrations in the associated biota and fish, which humans and other animals are assumed to consume.

IEM-2M is composed of two integrated modules that simulate mercury fate using mass balance equations describing watershed soils and a shallow lake. The mass balances are performed for each mercury component, with internal transformation rates linking Hg^0 , Hg^{2+} , and MeHg. Sources include wetfall and dryfall loadings of each component to watershed soils and to the water body. An additional source is diffusion of atmospheric Hg^0 vapor to watershed soils and the water body. Sinks include leaching of each component from watershed soils, burial of each component from lake sediments, volatilization of Hg^0 and MeHg from the soil and water column, and advection of each component out of the lake.

The nature of this methodology is basically steady with respect to time and homogeneous with respect to space. While it tracks the buildup of soil and water concentrations over the years given a steady depositional load and long-term average hydrological behavior, it does not respond to unsteady loading or meteorological events. There are, thus, limitations on the analysis and interpretations imposed by these simplifications. The model's calculations of average water body concentrations are less reliable for unsteady environments, such as streams, than for more steady environments, such as lakes.

The BAFs were used to estimate fish methylmercury concentrations based on measured concentrations of dissolved methylmercury in the water column. The distribution of the BAFs (Appendix D, Vol. III) was designed to estimate an average concentration of methylmercury in fish of a given trophic level from an average concentration of dissolved methylmercury in the epilimnion for a (single) randomly-selected lake in the continental U.S. The large amount of variability evidenced by the data and reflected in the output distributions arises from several sources, which were not quantified. Much of this variability depends on fish age, model uncertainty, and possibly the use of unrepresentative water column methylmercury measurements in the calculation of the BAFs.

Results of the Watershed Fate and Transport Analysis

For all facilities the contribution of the local source decreases as the distance from the facility increases. With the exception of the chlor-alkali plant, the facilities are generally predicted to contribute less than 50% to the total watershed soil concentration, with RELMAP (representing the regional anthropogenic sources) contributing up to 15% for the RELMAP 50th percentiles, and up to 60% for the RELMAP 90th percentiles.

The results for the MeHg water concentrations and trophic level 4 fish concentrations show a slightly higher contribution from the local sources. While the fractions are similar to those for watershed soil since the watershed serves as a mercury source for the waterbody, these values are slightly higher due to the direct deposition onto the waterbody.

The predicted fruit, leafy vegetable, and beef concentrations are generally dominated by the background values. For plants, this is because these products are assumed to take up most of the mercury from the air, and the local source usually does not impact the local air concentrations significantly. The exception is the chlor-alkali plant, for which the low stack results in higher mercury

air concentrations. The results for the beef concentrations are similar; however, there is a slightly higher contribution from the local source because the cattle are exposed through the ingestion of soil.

IEM-2M Model Sensitivity

For a specific atmospheric deposition rate, mercury concentrations in watersheds and water bodies can vary significantly. Several intrinsic and extrinsic watershed and water body characteristics influence the mercury concentrations in soil, water, and fish. These should cause significant variability in mercury concentrations between regions and among individual lakes within a region.

Mercury concentrations in watershed soils are strongly influenced by atmospheric loading and soil loss processes. The influence of plant canopy and roots in mediating both the loading to the soil and the loss from the soil is not well characterized at present, although published studies indicate its potential importance. Reduction of HgII in the upper soil layer appears to control the volatile loss of mercury, and variations in this reaction can cause significant variations in soil mercury levels. The factors controlling mercury reduction are not well characterized at present. Soil erosion from a watershed can vary more than 3 orders of magnitude depending on rainfall patterns, soil type, topography, and plant cover. High levels of soil erosion should significantly diminish soil mercury concentrations. Runoff and leaching are not expected to affect soil mercury concentrations significantly.

Total mercury concentrations in a water body are strongly influenced by atmospheric loading and, for drainage lakes, by watershed loading. Variations in watershed size and erosion rates can cause significant variability in lake mercury levels. Hydraulic residence time, the water body volume divided by total flow, affects the maximum possible level of total water column mercury for a given loading rate. Parameters controlling mercury loss through volatilization and net settling can also cause significant variations among lakes. Mercury loss through settling is affected by *in-situ* productivity, by the supply of solids from the watershed, and by the solids-water partition coefficient. DOC concentrations can significantly affect partitioning, and thus overall mercury levels. Mercury loss through volatilization is controlled by the reduction rate, which is a function of sunlight and water clarity. Reduction may also be controlled by pH, with lower pH values inhibiting this reduction, leading to higher total mercury levels.

Fish mercury levels are strongly influenced by the same factors that control total mercury levels. In addition, fish concentrations are sensitive to methylation and demethylation in the water column and sediments. A set of water body characteristics appear to affect these reactions, including DOC, sediment TOC, sunlight, and water clarity. Variations in these properties can cause significant variations in fish concentrations among lakes. Other factors not examined here, such as anoxia and sulfate concentrations, can stimulate methylation and lead to elevated fish concentrations. Fish mercury levels are sensitive to factors that promote methylmercury mobility from the sediments to the water column; these factors include sediment DOC and sediment-pore water partition coefficients.

Limitations of the Local Scale and Watershed Analyses

There are limitations associated with the fate and transport analyses. These have to do to a large degree with the current state-of-the-science concerning mercury fate and transport in the terrestrial and aquatic environments and variability between waterbodies. Some of the most important limitations are listed below.

- There is a lack of information characterizing the movement of mercury from watershed soils to water bodies and the rates at which mercury converts from one chemical species to another. There appears to be a great deal of variability in these factors among watersheds.

- There are not conclusive data on the amount of and rates of mercury methylation in different types of water bodies. In addition, there is a lack of data on the transfer of mercury between environmental compartments and biologic compartments; for example, the link between the amount of mercury in the water body and the levels in fish appears to vary from water body to water body.
- There is a lack of adequate mercury measurement data near mercury sources. Measurement data are needed to assess how well the modeled data predict actual mercury concentrations in different environmental media at a variety of geographic locations. Missing data include measured mercury deposition rates and measured concentrations in the atmosphere, soils, water bodies and biota.
- The IEM-2M has not been validated with site-specific data. The model was benchmarked against the independently-derived R-MCM, which itself has been calibrated to several Wisconsin lakes. When driven by the same atmospheric loading and solids concentrations, IEM-2M predictions of mercury concentrations compare well with those calculated by R-MCM for a set of Wisconsin lakes.

Conclusions Regarding Mercury Fate and Transport in the Environment

The uncertainty inherent in the modeled estimates arises from many individual assumptions present within the three models. Because of these uncertainties, U.S. EPA interpreted the model results qualitatively rather than quantitatively as follows.

The analysis of mercury fate and transport, in conjunction with available scientific knowledge, supports a plausible link between mercury emissions from anthropogenic combustion and industrial sources and mercury concentrations in air, soil, water and sediments. The critical variables contributing to this linkage are these:

- the species of mercury that are emitted from the sources, with Hg^0 mostly contributing to concentrations in ambient air and Hg^{2+} mostly contributing to concentrations in soil, water and sediments;
- the overall amount of mercury emitted from a combustion source;
- the watershed soil loss rates, including reduction and erosion;
- the water body loss rates, including outflow, reduction, and settling; and
- the climate conditions.

In addition, the analysis of mercury fate and transport supports a plausible link between mercury emissions from anthropogenic combustion and industrial sources and methylmercury concentrations in freshwater fish. The critical variables contributing to this linkage are the following:

- the species of mercury that are emitted, with emitted divalent mercury mostly depositing into local watershed areas and, to a lesser extent the atmospheric conversion of elemental mercury to divalent species which are deposited over greater distances;
- the overall amount of mercury emitted from a source;
- the watershed soil loss rates, including reduction and erosion;

- the water body loss rates, including outflow, reduction, and settling;
- the extent of mercury methylation in the water body;
- the extent of food web bioaccumulation in the water body; and
- the climate conditions.

From the analysis of deposition and on a comparative basis, the deposition of Hg^{2+} close to an emission source is greater for receptors in elevated terrain (i.e., terrain above the elevation of the stack base) than from receptors located in flat terrain (i.e., terrain below the elevation of the stack base). The critical variables are parameters that influence the plume height, primarily the stack height and stack exit gas velocity.

On a national scale, an apportionment between sources of mercury and mercury in environmental media and biota cannot be described in quantitative terms with the current scientific understanding of the environmental fate and transport of this pollutant.

Assessment of Exposure

The exposure Volume consists of two parts; the first examines exposures predicted to result from the emitted mercury, and the second estimates exposures that result from seafood consumption. The first part of the exposure assessment draws upon the modeling analyses described above which assessed the long range transport of mercury from emission sources through the atmosphere, the transport of mercury from emission sources through the local atmosphere, and the aquatic and terrestrial fate and transport of mercury at hypothetical sites. The exposure assessment used the results of the atmospheric, terrestrial and aquatic models to estimate the resulting exposures to humans and animals that were assumed to inhabit the hypothetical sites explained above. In the second part of the exposure Volume, exposure to mercury from seafood was estimated using various dietary surveys and measurements of mercury concentrations in seafood.

The exposure assessment, which was based on environmental fate and exposure modeling, addressed atmospheric mercury emissions from the four sources described earlier; MWCs, MWIs, utility boilers and chlor-alkali plants. It did not address all anthropogenic emission sources. In addition, anthropogenic discharges of mercury to waterbodies were not addressed.

Human Exposure

The following human exposure routes were included: inhalation, consumption of water, consumption of fish, beef, beef liver, cow's milk, poultry, chicken eggs, pork, lamb, green plants (e.g., leafy vegetables, potatoes, fruits, grains and cereals) and ingestion of soil. Dermal exposures that resulted from contact with soil and water, as well as exposure through inhalation of resuspended dust particles and exposure through the consumption of human breast milk were not evaluated. The only exposure route considered for wildlife was the consumption of freshwater fish.

Consumption of fish is the dominant pathway of exposure to methylmercury for fish-consuming humans and wildlife. There is a great deal of variability among individuals in these populations with respect to food sources and fish consumption rates. As a result, there is a great deal of variability in exposure to methylmercury in these populations. The anthropogenic contribution to the total amount of methylmercury in fish is predicted to be, in part, the result of anthropogenic mercury releases from industrial and combustion sources increasing mercury body burdens in fish. Existing background

mercury concentrations are also predicted to contribute to methylmercury concentrations in fish. As a consequence of human and wildlife consumption of the affected fish, there is an incremental increase in exposure to methylmercury. Due to differences in fish consumption rates per body weight and differences in body weights among species, it is likely that piscivorous birds and mammals have much higher environmental exposures to methylmercury than humans through the consumption of contaminated fish. This is true even in the case of fish consumption by humans who consume above average amounts of fish. The critical variables contributing to these outcomes are these:

- the fish consumption rate;
- the body weight of the individual in relation to the fish consumption rate; and
- the rate of biomagnification between trophic levels within the aquatic food-chain.

A current assessment of U.S. general population methylmercury exposure through the consumption of fish is provided in Chapter 4 of Volume IV. This assessment was conducted to provide an estimate of mercury exposure through the consumption of fish to the general U.S. population. It is a national assessment rather than a site-specific assessment. This assessment utilizes data from the Continuing Surveys of Food Intake by Individuals (CSFII 89-91, CSFII 1994, CSFII 1995) and the third National Health and Nutrition Examination Survey (NHANES III) to estimate a range of fish consumption rates among U.S. fish and shellfish eaters. Per capita, per user (only individuals who reported fish consumption during the survey period) based on a single-day's intake, and month-long per user were considered. The month-long per user projections reflect the combined frequency distributions of NHANES III frequency of fish/shellfish consumption data and single day's data for per user consumption patterns. For each fish-eater, the number of fish meals, the quantities and species of fish consumed and the self-reported body weights were used to estimate mercury exposure on a body weight basis. The constitution of the survey population was weighted to reflect the actual U.S. population. Results of smaller surveys on "high-end" fish consumers are also included.

These estimates of fish consumption rates were combined with species-specific mean values for measured methylmercury concentrations. The marine fish methylmercury concentration data were obtained from the National Marine Fisheries Service Database. The freshwater fish methylmercury concentration data were obtained from Bahnick et al., (1994) and Lowe et al., (1985). Through the application of specific fish preparation factors (USDA, 1995), estimates of the range of methylmercury exposure from the consumption of fresh water fish were prepared for the fish-consuming segment of the U.S. population. Per body weight estimates of methylmercury exposure were determined by dividing the total daily methylmercury exposure from this pathway by the self-reported body weights of individuals in the USDA surveys and recorded body weights in the third NHANES data. The species of fish/shellfish consumed by children were identified from the 24-hour recalls on children in the USDA surveys and in the third NHANES.. The results of this analysis show that on a per kilogram body weight basis children have higher average exposure rates to methylmercury through the consumption of fish than adults. The higher exposures to children are considered biologically meaningful because month-long mercury exposures considerably in excess of the RfD are observed among some children. At the RfD or below, exposures are expected to be safe. The risk following exposures above the RfD is uncertain, but risk increases as exposures to methylmercury increase.

Wildlife Exposure

In terms of predicted methylmercury intake on a per body weight basis, the six wildlife species considered in this analysis can be ranked from high to low as follows:

- Kingfisher
- River Otter

- Loon, Mink, Osprey
- Bald Eagle

Methylmercury exposures for the most exposed wildlife species (the kingfisher) may be up to two orders of magnitude higher than human exposures from contaminated freshwater fish (on a kilogram fish consumed per body weight basis). This assumes that the fish within different trophic levels of a given lake are contaminated with the same concentrations of methylmercury.