Mercury in the Environment: A Volatile Problem

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Mercury is a persistent and naturally occurring metal that has provoked substantial concern because methylmercury (an organic form) accumulates in fish and can cause subtle neurological deficiencies in children who have been exposed to it in the womb.\(^1\) Forty-one states now advise anglers to limit wild fish consumption because of contamination by methylmercury.\(^2\)

by Randall Lutter and Elisabeth Irwin
Accordingly, the U.S. Food and Drug Administration is under pressure to reduce its permissible level of mercury in fish sold in the United States. To address concern about mercury, several senators and President George W. Bush have proposed new legislation to cut emissions of pollutants from power plants, which are the biggest anthropogenic source of mercury in the United States.

However, these different parties disagree about how mercury should be regulated. The controversy is likely to grow through December 2004, which is the deadline for the U.S. Environmental Protection Agency (EPA) to regulate emissions following the maximum achievable control technology (MACT) provisions of the Clean Air Act. This proposed regulation has faced some opposition because it is relatively costly.

In general, established U.S. regulatory policy suggests that regulatory decisions to manage risks should carefully assess the costs of controls and the resulting improvements to human health and the environment. However, attempts to implement this policy in the case of mercury are complicated by significant scientific uncertainty about the role of natural and anthropogenic sources of environmental mercury, how mercury is transported through the environment and where it eventually rests, the processes that produce methylmercury, the effects of methylmercury on ecosystems, and the nature and scope of mercury-related risks to human health.

The neurotoxic effects of methylmercury on children’s health evoke dread and prompt reform proposals based on emotion rather than on science. However, the magnitude of risk depends on the degree of exposure to mercury, and fortunately, exposure generally appears small in the United States. Because of the uncertainty about these factors, identifying emissions limits that balance costs and benefits will be challenging to policy makers. Nonetheless, the available evidence suggests that even deep cuts in mercury emissions are unlikely to bring large benefits to public health or ecosystems. A stringent and costly cap on emissions may not be the best policy.

In examining the problem of mercury, it is necessary to review the current state of scientific understanding. Weaknesses and strengths should be identified—as should areas in which additional information would be of high value to policy makers. This article discusses mercury in the environment, human health effects, and ecological effects, and it examines the merit of past and prospective regulatory programs.

Mercury in the Environment

Mercury is present in the environment due to human activity as well as natural sources such as volcanoes and forest fires. The scope of mercury releases relevant to determining the causes of contamination in U.S. waters may be regional or even global rather than local, because mercury travels long distances in the air. Table 1 on page 27 summarizes key properties and the transport and fate of different forms of mercury. Forty percent (32 metric tons (t)) of the mercury deposited from the air onto U.S. water and soil in 1995 came from the global mercury reservoir (the amount of mercury circulating worldwide at any one time); the other 60 percent came from anthropogenic sources in the United States.

<table>
<thead>
<tr>
<th>Property</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury deposited from the air in 1995</td>
<td>32 metric tons (t)</td>
</tr>
<tr>
<td>Global mercury reservoir</td>
<td>4,900 t</td>
</tr>
</tbody>
</table>

There is also substantial uncertainty about the share of worldwide emissions that originates from human activity. One study concluded that natural sources, industrial sources, and the “recycling” of anthropogenic mercury each account for about one-third of the mercury burden in the global atmosphere at a given moment. Recycling occurs when mercury in water volatilizes and contributes to the buildup of atmospheric mercury concentrations.

Mercury releases from ongoing human activity in the United States can be divided into four broad categories. These include “area sources” such as landfills, dental preparations, and laboratory use; combustion processes, including coal-fired power generation,
medical waste incinerators, and municipal waste combustors; some manufacture of metals, alkali, and cement; and other various industrial processes, from pigment manufacture to geothermal power generation. EPA estimated that emissions from these source categories generated 2.76 t, 112.3 t, 12.67 t, and 1.16 t of environmental mercury per year, respectively, in 1994–95. Thus, combustion sources accounted for nearly 90 percent of total U.S. anthropogenic emissions. In recent years, EPA has regulated medical waste incinerators, municipal waste combustors, and hazardous waste combustors (see Table 2 below). When these regulations are fully implemented in the fall of 2002, EPA estimates annual mercury emissions of about 54 t lower than they would be without these regulations.

Mining in the past has raised mercury concentrations in some areas. Releases of quicksilver mercury in the hydraulic placer-gold mines of the Sierra Nevadas added 1,360 t to 3,630 t of mercury to the environment from the 1860s through the early 1900s. According to the U.S. Geological Survey (USGS), “High mercury levels in fish, amphibians, and invertebrates downstream of the hydraulic mines are a consequence of historic mercury use.”

**Methylation**

Bacteria in water bodies transform water-borne elemental, divalent, or inorganic mercury into methylmercury (CH₃Hg⁺), the organic form that accu-

### Table 1. Forms of mercury

<table>
<thead>
<tr>
<th>Key properties</th>
<th>Elemental or metallic (Hg⁰)</th>
<th>Divalent or mercuric (Hg²⁺)</th>
<th>Methylmercury (CH₃Hg⁺)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport and fate</td>
<td>95 percent of atmospheric mercury is Hg⁰ vapor.</td>
<td>Bound to airborne particles Comprises 5 percent of atmospheric mercury Found in soil and water as a number of complex ions May form inorganic mercuric salts</td>
<td>Lipophylic ion produced by bacteria in the water column or sediment Nearly all mercury in fish is methylated.</td>
</tr>
<tr>
<td>Date issued</td>
<td>Municipal waste combustors</td>
<td>Medical waste incinerators</td>
<td>Hazardous waste combustors</td>
</tr>
<tr>
<td>Date issued</td>
<td>25 August 1997</td>
<td>15 September 1997</td>
<td>13 September 1999</td>
</tr>
<tr>
<td>Compliance date</td>
<td>19 December 2000</td>
<td>15 September 2002</td>
<td>30 September 2002</td>
</tr>
<tr>
<td>Projected annual emissions cuts</td>
<td>38 metric tons</td>
<td>13 metric tons</td>
<td>3 metric tons</td>
</tr>
<tr>
<td>Annual emissions cuts as a percentage of preregulation levels</td>
<td>78%</td>
<td>94%</td>
<td>55%</td>
</tr>
</tbody>
</table>


### Table 2. Recent U.S. mercury regulations

<table>
<thead>
<tr>
<th>Date issued</th>
<th>Municipal waste combustors</th>
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mulates as it moves into higher levels of the food chain. Methylation occurs both in sediment and in the water column after mercury has entered the aquatic environment through methods such as atmospheric deposition, runoff, and groundwater flow from the upper levels of soil. However, not all mercury that enters a water body undergoes methylation. Rates of methylation vary with the aquatic environment and—due to limited understanding of the factors that influence methylation—are subject to significant scientific uncertainty.

Although there is a large degree of doubt about the processes that methylate mercury, various studies suggest that the most important factors influencing methylation may be chloride, sulfate, dissolved organic carbon, calcium, and pH. A study published in Environmental Science & Technology concludes that methylmercury principally accumulates in phytoplankton as it takes up uncharged chloride complexes. Phytoplankton is subsequently ingested by noncarnivorous fish, beginning the journey of methylmercury up the food chain and its process of bioaccumulation.

This study also cites pH as a primary determinant of methylmercury. Low pH may increase bacterial methylation rates, therefore increasing methylmercury levels. Typically, higher methylmercury levels in fish tissue are found in more acidic waters. Sulfate appears to be a critical factor in the methylation process because sulfate-reducing bacteria stimulate methylmercury production. Recent USGS studies in the Florida Everglades region have found a correlation between sulfate levels and methylmercury concentrations. While various processes can methylate mercury, USGS reports that "scientists generally agree that methylation by sulfate-reducing bacteria is most important." EPA has listed dissolved organic carbon as a characteristic of water bodies that affects both methylation and demethylation (the process that reverses methylation) in the water column. However, USGS reports, "Depending on local conditions, the amount of dissolved organic carbon—mercury binding can either increase or reduce mercury uptake by organisms." Finally, high calcium levels may reduce the bioavailability of methylmercury because calcium cations may compete with metals such as mercury for cellular binding sites.

Land use also affects the mercury concentrations that are available for methylation. Land under cultivation may be a proxy measure of erosion, which transports mercury from the soil to local water bodies. EPA notes that "[b]oth watershed erosion and direct atmospheric deposition can be important sources of mercury to the water body, depending on the relative sizes of the water body and the watershed." In addition, the amount of land under cultivation may serve as an indicator of the degree to which fungicides containing mercury are used for agriculture. In EPA's summary of studies in Lake Champlain, it reported that "[u]rban and agricultural systems may retain less atmospheric mercury than forested systems," thus transporting more mercury to water, where it can be methylated.

Methylmercury, which constitutes the vast majority of all mercury found in fish, accumulates at higher concentrations at higher levels in the food chain because of its affinity for fatty tissues. Figure 1 on this page depicts the cumulative distribution of mercury concentrations in all fish, all largemouth bass, and all yellow perch based on an EPA study of mercury in nearly 82,000 fish caught from 1990 to 1995 in 5,000 locations in 3,200 water bodies. These two broadly distributed and commonly eaten species illustrate how concentrations differ across species. Although 45 percent of all fish and 75 percent of yellow perch have mercury concentrations less than 0.3 parts per million (ppm), only 25 percent of largemouth bass have concentrations less than this value. EPA's water-quality standard for methylmercury is 0.3 ppm, which the agency recently established to "protect consumers of fish and shellfish among the general population."

**Transport**

Atmospheric deposition appears to be the primary means of environmental mercury contamination. Recent research

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**Figure 1. Mercury concentrations in fish**

![Graph showing mercury concentrations in different fish species](image)

NOTE: The vertical line marks 0.3 parts per million, the fish tissue concentration that corresponds to the U.S. Environmental Protection Agency’s (EPA) water-quality standard. This figure maintains EPA's conservative assumption that mercury concentrations too low to detect are equal to the limit of detection. These limits of detection vary among states.

demonstrates how levels of mercury deposition have varied over time with volcanic eruptions, gold mining, and industrialization (see Figure 2 on this page). Although mercury deposition can occur in both wet and dry forms, EPA has concluded that deposition through precipitation is the primary means of transport between the atmosphere and the Earth’s surface. Studies of Lake Michigan suggest that about 80 percent of total deposition is wet.

However, the determinants of wet mercury deposition in the United States are poorly understood. The National Acid Deposition Program takes field measurements of wet mercury deposition in 55 locations. It is interesting to compare this program’s data from the late 1990s with predictions from EPA’s Regional Lagrangian Model of Air Pollution (RELMAP) modeling, which EPA derived using emissions from 1994–95 and weather from 1989. Figure 3 on page 30 shows that field measurements of the annual average wet mercury deposition and RELMAP estimates for wet and dry deposition have little correlation and, thus, that mercury deposition is not predictable.

Also uncertain is the process by which mercury is removed from the aquatic environment. Mercury can be carried downstream or volatilize into gaseous elemental mercury from its divalent form (Hg\(^{2+}\)). EPA found that sedimentation may be the dominant process by which mercury leaves a water body.

**Effects on Human Health**

The health effects of mercury are presumed to be irreversible. The U.S. Centers for Disease Control recently reported new data on levels of mercury in the blood and hair of young children and women of childbearing age, based on the 1999 National Health and Nutrition Examination Survey (NHANES), which was random and nationally representative. The 90th percentile of mercury in hair for 702 women was 1.4 ppm, an estimate in line with earlier surveys of hair mercury levels in nonrandom samples of U.S. residents. The study reports that “approximately 10 percent of women have mercury levels within one tenth of potentially hazardous levels indicating a narrow margin of safety for some women and supporting efforts to reduce methyl mercury exposure.” A more precise statement about the number of women exposed to elevated levels is difficult because NHANES does not provide estimates of mercury exposure in certain highly exposed groups such as some Native Americans and others who eat large amounts of fish.

![Figure 2. A 270-year record of mercury deposition](image-url)
Careful epidemiological studies of children exposed in the womb to higher methylmercury concentrations than those typically found in the United States have reached sharply different conclusions. A study of children in the Seychelles Islands found no association between methylmercury and a broad variety of health effects. A study in the Faroe Islands found statistically significant associations in the domains of language, attention, memory, and—to a lesser extent—visuospatial and motor functions, but it did not examine broader measures of performance such as IQ tests. A study of New Zealand children found declines in summary measures of neurological performance, but only if a single highly exposed and apparently healthy child is omitted from the analysis.

In evaluating why such studies have different outcomes, the National Research Council (NRC) reported that there “do not appear to be any serious flaws in [their] design and conduct.” In a 2000 review of these studies, NRC estimated that in the United States, “60,000 newborns annually might be at risk for adverse neurodevelopmental effects from in utero exposure to methylmercury.” NRC derived this estimate as the product of the number of female fish-consumers in the United States aged 15 to 44 years, 5 percent (thought to correspond to those consuming more than 100 grams per day of fish), and the birth rate. This widely cited estimate is intended to represent the number of children born to mothers who may be exposed to mercury at levels exceeding the current reference dose of 0.1 microgram (µg) per kilogram body weight per day. However, the chair of NRC’s Committee on the Toxicological Effects of Methylmercury, Robert Goyer, cautioned, “That number should not be interpreted as an estimate of the annual number of cases of adverse neurodevelopmental effects.”

An earlier survey, published in 1997, provides estimates of the decline in mercury exposure in U.S. women that would result from the hypothetical elimination of mercury in fish. These results, which are similar to those of the NHANES survey, indicate that geometric mean mercury concentrations in the hair of respondents reporting some seafood consumption and no seafood consumption were 0.36 ppm and 0.24 ppm, respectively (with geometric standard deviations of 2.5 ppm and 2.6 ppm, respectively).

Because 55 percent of the women who responded to the 1997 survey reported eating fish, and approximately 3.9 million children are born annually in the United States, these distributions imply that the elimination of mercury from fish would reduce the number of children born to women with hair mercury levels of 1–2 ppm by 100,000, children born to women with levels of 2–4 ppm by 30,000, and children born to women with levels greater than 4 ppm by 6,000. Presuming that mercury exposure lower than 1 ppm has negligible effects, children who would have been born to women with levels of 1–2 ppm would experience reductions in potentially hazardous in-utero exposure of 0.5 ppm on average. Exposure of children who would have been born to mothers with mercury levels of 2–4 ppm would be reduced by 1.8 ppm, and exposure among children who would have been born to mothers with levels greater than 4 ppm would be reduced by 4.4 ppm. Because these exposure levels are for the hypothetical total elimination of mercury in fish, actual reductions from foreseeable regulations would be smaller.

Assessing potential health improvements for children requires information
about the relationship between exposure and health effects. A 1999 study by Phillipe Grandjean and colleagues and a 1998 study by Kenny Crump and colleagues provide estimates of these relationships for neurological performance measures of finger-tapping, hand-eye coordination, reaction time, delayed recall of words, and two specialized tests: the Boston naming test and McCarthy’s Perceptual Performance Scale. According to these studies, reducing mercury in a mother’s hair by 4.4 ppm—reduction to the “negligible” level from the average level experienced by the 6,000 children in the most exposed group—would improve reaction times by only 22 percent of a standard deviation. (In assessing these health effects, it should be noted that four standard deviations represents a typical range of behavior in a population given a normal distribution.) All of the other health effects for which Grandjean or Crump report quantitative exposure response information would improve by less than 20 percent of a standard deviation. (In assessing these health effects, it should be noted that four standard deviations represents a typical range of behavior in a population given a normal distribution.)

A 1995 study of 1,833 middle-aged and older Finnish men with average hair mercury levels of 1.9 ppm found mercury exposure to be associated with elevated risks of heart attacks and death. Study authors Jukka Salonen and colleagues estimated that subjects with hair mercury levels greater than 2 ppm had a 70-percent greater risk of suffering acute myocardial infarctions than subjects with lower hair mercury levels. They also reported that the risk of death for men with hair mercury levels greater than 2 ppm was 93 percent higher than that of men with lower levels.

There are several reasons for skepticism about the results of this study. It has not been independently replicated in other samples, so the results may reflect something peculiar to the Finnish population. In addition, the study did not show that relative risk increases systematically with exposure, as should generally be the case. Indeed, the paper’s conclusions are contrary to those of an epidemiological study published in 1996 of people exposed in Japan during the infamous 1950s Minamata episode. The 1996 study found no excess risk of overall mortality or noncancer deaths, even though exposure to mercury was vastly greater than that of Finnish men in the 1995 study.

Finally, the Finnish study did not assess whether mercury in hair was predominantly methylmercury—an important issue because nearly all mercury in fish is methylmercury. Mercury from other sources could have played a significant role, as is suggested by some aspects of the data. Salonen and colleagues report hair mercury levels that were 260 percent higher than those reported by a 1996 study of New Jersey women (1.9 ppm versus 0.53 ppm)—but levels of mercury in the diet that were only 20 percent greater (7.6 µg per day versus 6.3 µg per day). Because fish intake among the Finnish men correlates only weakly with mercury in hair, some of the variation in hair mercury levels may be due to factors other than fish consumption. Thus, heart attack risks from mercury exposure merit greater attention from researchers—but not from policy makers at this point.

It is difficult to compare the health effects of mercury with potential health problems caused by other environmen-
tal factors, but the effects described above seem less severe than some others such as cancers, fatalities from respiratory ailments, or IQ deficits related to lead poisoning. Efforts to reduce the risk for health effects such as these are currently being pursued through environmental policies.

**Effects on the Environment**

Assessing the environmental effects of mercury is intrinsically difficult because of the complexity of ecosystems, the existence of multiple sources of stress, and the many endpoints where mercury might have adverse effects. In its 1997 *Mercury Study Report to Congress*, EPA described environmental effects by noting that environmental mercury may adversely affect reproduction of loons—fish-eating birds in which effects should be most easily detectable because of the bioaccumulative properties of methylmercury. However, common loon populations grew at an annual rate of 2.6 percent between 1966 and 1999.\(^6^3\) Populations of other fish-eating birds grew at even faster rates.\(^6^4\) Such high growth rates and the understanding that there appears to be no correlation between areas of low population growth and areas of high mercury deposition suggest that the ecological benefits of reducing mercury emissions may not be great.\(^6^5\)

Florida panthers also may be at risk of methylmercury poisoning, because high mercury concentrations in their habitat have caused high mercury concentrations in their prey. According to EPA, “Mercury levels found in tissues obtained from dead panthers are similar to levels that have been associated with frank toxic effects in other feline species.”\(^6^6\) Over the last decade, however, the Florida panther population apparently has increased to 80 from between 30 and 50 as a result of introducing new panthers into the area to reduce inbreeding.\(^6^7\)

Although a recent screening-level assessment of mercury in southern Florida food webs suggested that 100 percent of alligators are exposed to methylmercury at concentrations that exceed toxic reference values for sensitive bird and mammal species, no data on its toxicity to alligators are available.\(^6^8\) No studies that quantitatively estimate the effect of methylmercury on the population of alligators or other indicator species are apparent.

**Mercury Controls**

Policy makers should take into account the environmental and health effects of mercury when they design new regulations to limit mercury releases. In the past several years, EPA has issued three regulations to limit mercury emissions (as shown in Table 2). The U.S. government has regulated a diverse set of possible uses of mercury under other laws, as listed in Table 3 on page 33. Concern about the environmental effects of mercury has prompted a variety of industry and state efforts to restrict the sale of certain products and implement disposal programs; these measures reduced industrial demand for mercury by 75 percent between 1988 and 1997.\(^6^9\) To date, 18 states have proposed 49 bills that would restrict or prohibit products that contain mercury; limit mercury emissions from power plants; or establish product-labeling requirements, health-warning standards for water bodies, or waste-management programs.\(^7^0\) Currently, only Indiana, Maryland, Minnesota,
and Maine have enacted these laws, but some states have instituted special programs to remove from use thermometers or other devices that contain mercury. EPA expressed its recent water-quality criteria for methylmercury in terms of fish tissue concentration—0.3 ppm—because fish consumption is the primary means of human exposure to methylmercury. EPA intends for its water-quality criteria program to provide a science-based maximum level for methylmercury that can be used by states and localities to promulgate local water-quality standards and by EPA as a basis for federal rulemaking to reduce mercury discharges under the Clean Water Act. States are not forced to adopt the EPA criteria, but under the Clean Water Act, they must adopt water-quality standards that are adequate for each water body’s designated use—such as swimming—and commensurate with “sound scientific rationale.” In addition, EPA must approve states’ standards. Thus, the practical impact of EPA’s criteria is likely to be high even though, strictly speaking, the criteria are not legally binding. However, because 55 percent of fish have mercury concentrations that exceed EPA’s water-quality criteria and there is no model predicting how much mercury emissions must be cut to reduce concentrations in fish tissue, compliance with EPA-approved water-quality standards might be quite difficult.

**Prospective Regulations**

Because coal-fired power plants are the largest unregulated source of anthropogenic mercury emissions in the United States, they are a favorite target of new regulation and legislation. A bill introduced by Senator Jim Jeffords (I-Vt.), chair of the Environment and Public Works Committee, would reduce

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**Table 3. U.S. mercury product regulations**

<table>
<thead>
<tr>
<th>Product</th>
<th>Role of mercury</th>
<th>Regulation or program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural products</td>
<td>Pesticide, bactericide, disinfectant, fungicide</td>
<td>Restricted and/or banned under U.S. Insecticide, Fungicide, and Rodenticide Act</td>
</tr>
<tr>
<td>Paints</td>
<td>Biocide to control microbial growth in paint cans and mildew on painted surfaces</td>
<td>Registrations for use of mercury in latex paint cancelled in 1990–91; mercury in antifouling paint for marine use banned in 1972</td>
</tr>
<tr>
<td>Pigments and dyes</td>
<td>Red coloring for plastic</td>
<td>Domestic production ceased in 1988, imports allowed</td>
</tr>
<tr>
<td>Cosmetics</td>
<td>Preservative, antimicrobial</td>
<td>Limited to eye area and concentrations under 65 parts per million&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Fluorescent lamps</td>
<td>Mercury vapor fluoresces under ultraviolet light</td>
<td>Spent lamps were added in 1999 to the Universal Waste Rule, implementing the Resource Conservation and Recovery Act (RCRA) to reduce risks that might pose threats over time in municipal solid waste landfills&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Batteries</td>
<td>Mercury offers high and lasting voltage in alkaline-manganese and zinc-carbon batteries, commonly used for cameras</td>
<td>Included in 1995 Universal Waste Rule of RCRA to divert them from municipal solid waste landfills&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Dental equipment</td>
<td>Forms alloys, binds compounds to form restorative material</td>
<td>Under the U.S. Food, Drug, and Cosmetic Act, dental mercury and amalgam alloys regulated separately by the U.S. Food and Drug Administration as Class I and II devices</td>
</tr>
</tbody>
</table>

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NOTE: Battery manufacturers have reduced mercury use by more than 90 percent since 1988.

International Mercury Regulation

An overview of mercury regulation in the European Union, Japan, and the United States reveals a variety of different approaches. Promoting uniformity, the 1998 United Nations Protocol on Heavy Metals set prescriptive numerical emissions limits for hazardous and municipal waste incinerators and directed parties to the protocol to set limits for medical waste incinerators. The European Union (EU) has approved the protocol, and the United States has accepted but not ratified it. The protocol does not mention the use of economic approaches such as the tradable mercury emissions permits proposed in the United States as part of the Bush administration’s Clear Skies Initiative. Because the protocol does not address mercury emissions from electricity generation or the regulation of mercury in lakes and rivers, it leaves room for ample differences in approaches across countries. See the table below for some approaches to mercury regulation in the United States, the EU, and Japan.

Separate from the UN protocol, in 1996 the European Council issued a directive ordering “limit values and alert thresholds” for a variety of air pollutants, including mercury. The directive resembles aspects of U.S. federal regulation in that it assigns to member states the responsibility to implement the limit val-

### Regulatory approaches

<table>
<thead>
<tr>
<th>Jurisdiction</th>
<th>Air emissions</th>
<th>Water</th>
<th>Methylmercury consumption reference dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>Regulated except for power utilities, for which legislation and regulation are pending.</td>
<td>Water-quality standard of 0.3 ppm in tissue of fish in U.S. waters</td>
<td>0.1 µg/kg/day</td>
</tr>
<tr>
<td>Japan</td>
<td>Mercury is identified as a “substance requiring priority action” under harmful air pollutant regulations, which specify duties such as accumulation of knowledge and voluntary reductions.</td>
<td>0.5 µg/liter for all public water bodies</td>
<td>Provisional tolerable weekly intake of 0.4 µg/kg/day</td>
</tr>
<tr>
<td></td>
<td>Proposed ambient air-quality standard of 0.05 µg/m³</td>
<td>Uniform National Effluent Standards permit 5 µg/liter</td>
<td></td>
</tr>
</tbody>
</table>

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h European Commission, note d above, page 5-23.

NOTE: ppm = parts per million; µg/kg/day = micrograms per kilogram body weight per day; m³ = cubic meter.
SOURCE: R. Lutter and E. Irwin.
In response to the directive, the European Commission proposed an ambient air-quality standard of 0.05 micrograms per cubic meter for elemental mercury to protect the general population from kidney cancer related to inhalation. However, the proposed standard is rarely exceeded in Europe. The United States and Japan do not have such a standard.

The United States has regulated all significant sources of mercury emissions in a manner consistent with the UN protocol—with one important exception. Mercury emissions from power plants are not addressed in the protocol and are unregulated in the United States, although legislation and regulation are pending. The EU also has not regulated mercury emissions from power plants.

Regulatory approaches to mercury in water differ. Japan has established safe levels of mercury in lakes and streams and has set efficient standards. The U.S. Environmental Protection Agency has set water-quality criteria in terms of the mercury concentration in fish tissue. It is notable that the U.S. standard of 0.3 parts per million (ppm) is more stringent than the World Health Organization and the Food and Agriculture Organization’s recommendations of 0.5 ppm. The United States and the EU have set standards for mercury in the effluent of a broad range of industrial sources.

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Emissions are from utilities. Figure 4 below illustrates how sources of mercury are linked to human health effects in the United States. EPA estimated that about three-fifths of mercury deposited in the United States in 1994–95 was emitted from U.S. anthropogenic sources and that the rest came from global or nonanthropogenic sources. The pending regulations discussed earlier would significantly reduce U.S. anthropogenic emissions below these levels.

Another factor to consider in efforts to limit exposure is that, despite important new research about how mercury enters the food chain, there is no accepted quantitative estimate of the relationship between mercury deposition and mercury concentrations in fish. To the authors’ knowledge, there is no quantification of such a link even for particular types of lakes. Although statistical studies have suggested that acidity, prevalence of wetlands, and mercury in the water column are associated with mercury concentrations in fish, to date they have not shown an association between mercury deposition and measures of mercury in fish. An innovative ongoing study in Canada that deliberately adds trace amounts of mercury to the area surrounding a small lake might elucidate this link, but its broader applicability to other ecosystems is unclear.

Finally, deposition in the United States affects only some of the fish consumed by U.S. residents. Mercury levels in marine fish from distant waters and in farmed fish that eat commercial feed are not affected by changes in U.S. emissions. Even mercury levels in seafood caught near the United States may be relatively insensitive to local deposition because of the complexity and geographic extent of marine food chains.

Some evidence suggests that most exposure to mercury, even among populations with high fish intake, comes from consumption of seafood caught in offshore waters where reductions in U.S. mercury emissions would have negligible impact. In New Jersey, for example, only 4 to 5 percent of all fish eaten is obtained recreationally, and only about 13 percent of that amount is freshwater fish, according to one study. (Ocean fish may be less likely to be affected by mercury from U.S. sources.) The study found that the two most commonly consumed types of seafood were tuna and shrimp, which together accounted for one-third of seafood consumption; no other category accounted for more than 12 percent. Yet these fish are predominantly from waters unaffected by U.S. emissions. More than 97 percent of all tuna marketed in the United States is caught on the high seas or imported from other countries; only about 3 percent of all shrimp marketed in the United States is caught within 200 miles of the Atlantic states that are downwind from utility plants. There is no assessment of how much of the mercury exposure among highly exposed individuals comes from fish sensitive to U.S. deposition.

**Sensible Approaches to Mitigating Risk**

The uncertain and incomplete scientific understanding about how mercury emissions harm public health and ecosystems handicaps government attempts at sensible regulation. Although scientific uncertainty is ubiquitous in environmental policymaking, there is a serious lack of knowledge about mercury, despite some insightful new research. The available data suggest that sharp cuts in mercury emissions from U.S. power plants will not result in large environmental and public health gains in comparison with gains from other high-priority environmental initiatives.
Based on survey evidence linking mercury in women's hair to their fish consumption and the exposure-response relationships from epidemiological studies, the hypothetical complete elimination of mercury from fish would benefit only a relatively small number of children. Approximately 6,000 children would experience improvements in specific, narrow measures of neurological performance (between 13 percent and 22 percent of a standard deviation)—a small change. Larger numbers of children would experience even smaller improvements, assuming that the exposure-response relationships are valid at lower levels of exposure. Even very sharp cuts in U.S. power plants’ mercury emissions would provide much more modest benefits because they would affect only one of many sources of mercury to which U.S. women are exposed.

Measuring these health gains against those from other environmental initiatives requires a difficult apples-to-oranges comparison, because the value of such changes in neurological performance has not been quantified. Nonetheless, the scope of health benefits due to reduced mercury emissions appears smaller than that of benefits from proposed cuts in sulfur dioxide and nitrogen oxides, which EPA estimates would prevent more than 10,000 deaths annually from respiratory and other ailments.

These potential benefits also appear small when considering the costs of EPA’s pending technology-based mercury regulations—from $1.1 billion to $1.7 billion annually. On a per-child basis, the costs of MACT standards would be on the order of $10,000, conservatively including all affected children and completely ignoring the limited effectiveness of cuts in U.S. utility emissions in reducing exposure to mercury in fish. While such comparisons sometimes suggest unsettling tradeoffs between corporate profits and children’s health, such suggestions are dubious here. The health effects are not changes in the health of identifiable children but are small differences in the risk that all children face. Moreover, utilities pass on to consumers the costs associated with emissions controls. Thus the tradeoff is really between the cost of reductions for collective U.S. consumers and the potential for subtle health improvements.

Multipollutant approaches such as the Clear Skies Initiative and Senator Jeffords’s proposal could reduce mercury more cost-effectively than mercury regulations alone because new controls on nitrogen oxides and sulfur dioxide provide “free” reductions in mercury emissions. However, the authors are unaware of estimates of the incremental cost of caps on mercury emissions, assuming cuts in nitrogen oxides and sulfur dioxide consistent with Clear Skies, Jeffords’s proposal, or other legislative initiatives. Thus it is premature to assess the economic merit of the mercury cuts in these proposals.

Economics and risk assessment can and should play a prominent role in public debate about the merit of environmental initiatives, although Congress and EPA consider many other factors in developing new legislation. The challenge to the research community is to improve understanding of the merit of mercury controls quickly enough to help Congress and EPA develop sensible limits for mercury emissions.

Coal-fired power plants are the largest unregulated source of U.S. anthropogenic mercury emissions. Multipollutant controls might prove effective in reducing mercury.

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NOTES

1. National Research Council (NRC), Committee on the Toxicological Effects of Methylmercury, Board on Environmental Studies and Toxicology, Commis-


10. Ibid.


16. Ibid.


18. Ibid., page 2-5.

19. Ibid.

26. USGS, note 24 above.
29. See, for example, ibid., page 2-6.
31. EPA, note 27 above, page 1-1.
32. EPA, note 27 above.
34. EPA, note 7 above.
35. Ibid., vol. 1, page 2-4.
38. EPA, note 7 above, vols. 2 and 3, page 4-2.
41. NRC, note 1 above, page 324.
42. FDA, EPA, DOE, NOAA, and CDC, note 40 above, page 140.
accretion and accelerated progression of carotid atherosclerosis among Finnish men. Although they report statistically significant associations between mercury hair content and atherosclerosis, they fail to assess the proportion of mercury that is methylmercury and therefore attributable to fish consumption.

59. This condition was one of Sir Bradford Hill’s (of Sir Bradford Hill) criteria for inferring that epidemiological associations are causal (Rosamond and Poole, note 57 above).


62. Salonen et al., note 55 above, Table 2.


64. For osprey populations, the survey-wide trend is 6.7 percent, and for double-crested cormorants, the survey-wide trend is 7 percent (ibid.).

65. Sauer, Hines, Thomas, Fallon, and Gough, note 63 above; see trend maps.


72. EPA, note 33 above, page 1,346.

73. EPA, note 27 above, Figure 4–2.


77. Ibid., pages 8–9.


84. Stern, Korn, and Ruppel, note 61 above, page 505.

85. Ibid., page 510. The study indicates that average mercury concentrations were 0.1 ppm for tuna and 0.11 ppm for shrimp.


87. The authors’ calculations used data from the Grinnell and Crump water samples.

88. See the comments of Peter Tsirigotis of EPA on 19 February 2002 at the AEI-Brookings Joint Center conference “Regulating Air Pollutants from Power Plants: What is Sensible?”

89. This upper-bound estimate of compliance costs of the mercury cap for the Clear Skies proposal is derived by conservatively assuming that EPA’s estimate of the marginal cost is also the average cost, which the agency did not report. Multiplying the 30-metric ton (t) reduc- tion in mercury emissions (from 43 t to 13 t) by the per- mit price estimate for the 13 t in 2018 ($14,440 per pound) gives $972 million. See EPA, “Clear Skies Ini- tiative,” Regional Summary Report (2002), accessed via the Clean Air Markets—Programs and Regulations page at http://www.epa.gov/airmarkets/epa-impresults. html#downloadresults on 23 July 2002 (download imp2000s153d.c).

90. Ibid.

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