



MERCURY CONTROL FOR COAL-FIRED POWER PLANTS

by Paul Haase

The Story in Brief

After some 15 years of study, the U.S. Environmental Protection Agency issued final rules on March 15, 2005, for regulating mercury emissions from coal-fired power plants. The new regulations require a reduction of mercury emissions by 70%, phased in over the coming 12 years. No commercial technologies yet exist for fully controlling mercury emissions from coal plants, but several approaches show good potential in full-scale tests and some are nearing market readiness. EPRI, working closely with DOE and the power industry, has conducted extensive mercury control research and developed some of the most promising technologies.

As late as the 1950s, mercury permeated American life. Parents annually administered mercurous chloride, or calomel, to children as a laxative and dewormer. Mercury-bearing calamine lotion soothed itches; mercuriochrome sterilized wounds; mercurio-organic wonder-compounds preserved seeds and wood. Mercury even helped smooth the ride of luxury cars—one Studebaker model employed some 40 pounds of it. Although the risk of mercury vapor as a human neurotoxin was not unknown—the U.S. Public Health Service banned mercury from felt-making in 1941—few concerned themselves with mercury waste when children sought out spilled blobs of mercury to play with. Factories discharged mercury directly into rivers and lakes, hospitals and laboratories discarded broken mercury thermometers with the trash, incinerators and power plants sent mercury skyward.

Quick Change for Quicksilver

By the 1960s, recognition of mercury as a toxin and environmental danger turned the public attitude toward mercury up-

side-down. The U.S. Environmental Protection Agency (EPA) named mercury as a potentially hazardous air pollutant in 1971, and the Safe Drinking Water Act in 1974 established limits on mercury in public water systems. The 1976 Resource Conservation and Recovery Act identified mercury as a hazardous material and mandated safe management and disposal (including for emissions from combustion). Regulators have since refined and expanded pollution laws to eliminate mercury in batteries and paint, reduce emissions from municipal incinerators and industry, and control most other sources. Today, domestic use of mercury has dropped to well below one-fifth of its 1964 peak, according to EPA estimates. The worst human health problem, discharging mercury-containing waste into water where it can contaminate food fish, has been virtually eliminated in the United States.

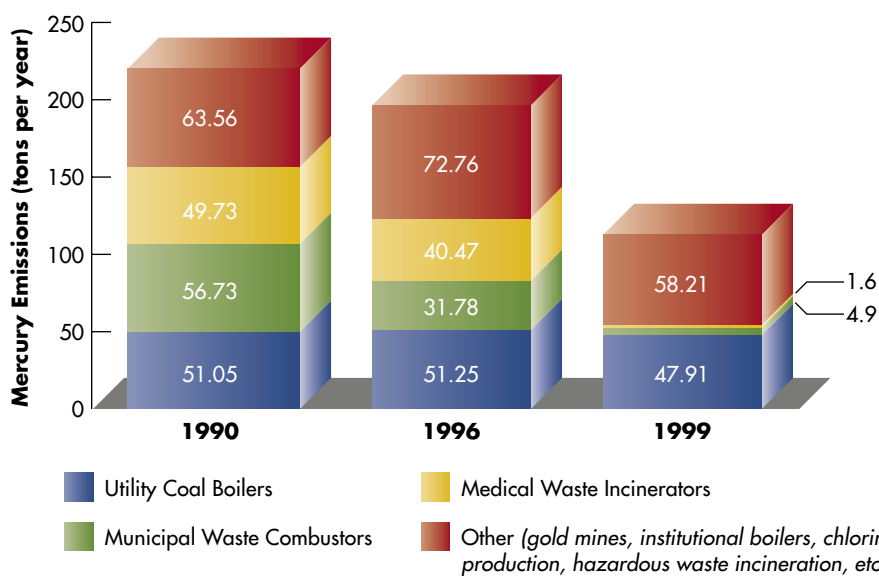
Mercury emissions to the air were the last to be regulated, with initial rules focusing on two of the most obvious sources—medical waste incineration and the burning of municipal waste. As a

result, U.S. mercury air emissions have fallen by half since 1990, to about 115 tons per year, and continue to decline. This progress has focused attention on a third substantial source of mercury air emissions: the nation's 600 or so large coal-fired power plants. Mercury from these plants accounts for 45–50 tons of domestic mercury air pollution annually. And while the releases have remained steady at this level for the past 15 years, as other mercury emissions have fallen, coal plants have come to represent a greater and greater fraction—now about 40%—of total domestic emissions. In a global accounting, mercury emissions from U.S. coal plants represent less than 1% of natural and human-caused sources.

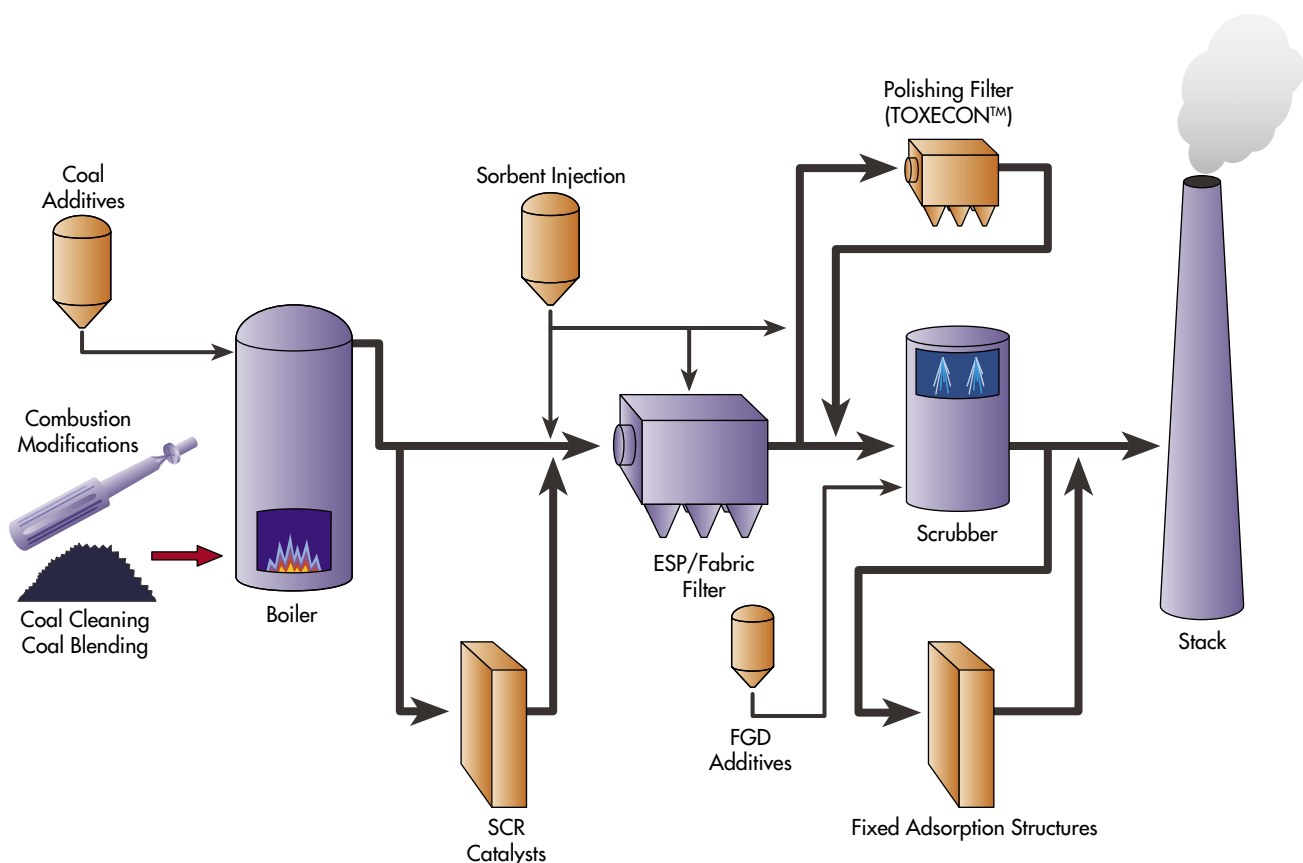
The Clean Air Mercury Rule

EPA began studying coal plants as the last significant source of mercury emissions in 1997 and, after some controversy (see sidebar, p. 24), formally issued its Clean Air Mercury Rule, or CAMR, to regulate coal plant emissions on March 15, 2005. This two-phased rule creates performance standards and establishes permanent, declining caps on mercury emissions from coal plants. The Clean Air Mercury Rule marks the first time EPA has regulated mercury emissions from coal-fired power plants and makes the United States the first country in the world to regulate these emissions.

The mercury rule is intended to work in tandem with EPA's new Clean Air Interstate Rule, or CAIR, which tightens existing regulations on two other coal plant emissions: sulfur dioxide (SO₂), which contributes to acid rain and fine particulates, and nitrogen oxides (NO_x), a precursor of ozone (sometimes referred to as smog) and also of fine particulates. The aim is that by 2018, these two rules will reduce coal plant emissions of mercury by about 70%, to 15 tons per year nationwide. Reductions will be achieved through a market-based "cap-and-trade" program similar to that of EPA's highly successful Acid Rain Program, which in the 1990s delivered its environ-



U.S. mercury air emissions have been substantially reduced over the last 15 years, in part through regulation of medical waste incineration and municipal waste combustion. EPA's Clean Air Mercury Rule, issued earlier this year, will put limits on emissions from the nation's 600 or so large coal-fired power plants.



A number of approaches are being investigated for controlling mercury emissions from coal-fired power plants. Potentially beneficial modifications of the fuel or combustion process include coal cleaning, coal blending, and control of the mixing of air and coal during combustion. Options to increase the removal of mercury by scrubbers, which are already on the system to control SO₂ emissions, include adding an SCR (which also reduces NO_x emissions) or catalysts and additives designed specifically to convert the mercury to a scrubbable form. Finally, several mercury-specific approaches are being developed— injection of activated carbon or other sorbent material into the flue gas, sorbent-based polishing filters, and fixed adsorption structures.

mental improvements faster and much more inexpensively than anticipated.

Under the cap-and-trade program for mercury, EPA will assign individual states (and two Native American tribes with coal-fired power plants on their lands) an emissions budget for mercury. Each state will determine how to regulate its coal plants to meet this emissions budget. During the phase-in period, plants that meet emissions limits ahead of time can bank these credits for use later or can sell them to those that will not be able to meet their limits on time. After the 2010 Phase 1 compliance date and the 2018 Phase 2 compliance date, companies whose plants in aggregate control mercury emissions below their allocated limit will be able to

sell the “over-control” amount to companies whose plants cannot achieve their allocated limits cost effectively.

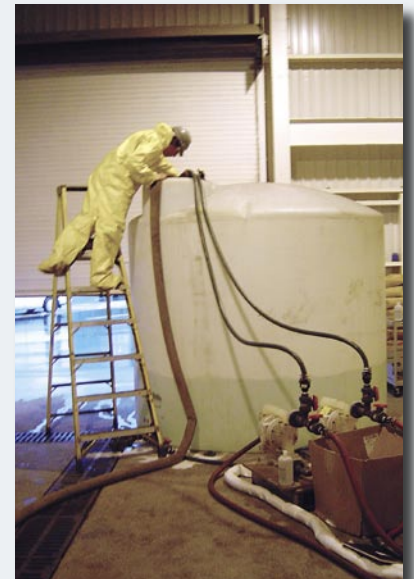
The Capture Challenge

Now that EPA has ruled, coal plant owners and operators will need the means to better capture mercury emissions. Some improvements can be achieved by modifying existing SO₂ or NO_x control devices, but new approaches will be required to meet the final 2018 emission limits. As yet, no technology designed specifically to control mercury in coal plants is in use anywhere in the world, or has even undergone long-term testing.

To develop and demonstrate such technologies, EPRI is working with the U.S.

power industry and government organizations in a broad program of research and field testing at power plants. The large-scale mercury field testing in the United States was made feasible through significant funding and technical management by the U.S. DOE’s National Energy Technology Laboratory (NETL). Important collaborators are the host sites, the developers of the control technologies themselves, and the engineering firms conducting the tests. The overall effort builds on 15 years of EPRI mercury control research.

This important work could not be done without the contributions of the many power companies that offer their plants for field testing. “With federal regula-



The DOE-NETL field test program, which benefits from 15 years of EPRI mercury research, is exploring the effectiveness of a dozen mercury control strategies at over 30 utility plants. The extensive test program is scheduled to continue through 2007. (Photos courtesy URS Corp.)

tion now in place, full-scale testing at the power plant is a critical step in the development of potential technologies,” says EPRI President and CEO Steve Specker. “We cannot simulate these conditions in the laboratory and need to determine whether performance in the field can be sustained over a period of time without interfering with the plant’s operation.” The commitment of the field-test utilities

is of tremendous value, considering that a typical coal plant generates tens of thousands of dollars worth of electricity each hour—electricity and revenue that are lost if the plant is shut down to install or tend experimental equipment.

Most emission control strategies for mercury focus on boosting the mercury-capture effectiveness of the standard pollution control equipment already installed

at existing coal-fired power plants. This equipment includes flue gas catalysts to control NO_x, scrubbers and spray dryers to capture SO₂, and particulate filters to catch fly ash. These existing technologies capture about 35% of the mercury in flue gases, on average, but performance varies widely from plant to plant. Of the approximately 75 tons of mercury found in the tens of millions of tons of coal

delivered to power plants each year, about 25–30 tons are captured in existing pollution controls and 45–50 tons are emitted to the air.

Key to capturing emissions is the chemical form of the mercury—elemental or ionic—as it passes through each pollution control device. Ionic mercury, which is soluble in water, is absorbed in scrubbers, whereas elemental mercury is not. Thus, the mercury-control challenge in a coal plant is primarily one of chemistry. For plants with existing or impending SO₂ controls, the objective is to increase the proportion of ionic mercury—either during combustion of the coal or in the flue gas itself—by some kind of oxidation process. Those without SO₂ controls may need to install mercury-specific technology.

The choice is neither simple nor obvious. Chemistry and economics dictate that most coal plants will employ one mercury control approach rather than a combination, and the choice must be determined plant by plant because of the wide difference in coal plant designs, the pollution equipment they have, and the coal types they burn. “For any given regulation, we must have options for all the combinations of coals and existing air pollution controls used by the industry,” says George Offen, EPRI’s technical executive for air emissions. “It’s no ‘one-size-fits-all’ situation.”

Modifying Coal and Combustion

Mercury control starts with the source, coal. This presents the first difficulty, because coal is a sedimentary rock that has no fixed composition. In coal, as in many similar sediments, mercury occurs as a trace element at about one part per million. Although coals come in a great variety—the chemistry and characteristics varying with the amount of heat and pressure a coal has experienced over its long history—most U.S. power plants burn one of two broad types, according to which is regionally available. In the East, plants generally fire harder bituminous coal,



Sunflower Electric's Holcomb Station near Garden City, Kansas, was host to a full-scale field test of sorbent injection for mercury capture under the DOE-NETL program. Conventional sorbents injected into the flue gas duct (far left) before the plant's spray dryer unit achieved only modest results in removing mercury. However, use of a new, chemically enhanced sorbent removed 90% of the mercury at low-to-moderate injection rates. The sorbent is collected by the plant's fabric filter, and the cleaned flue gas exits the stack at right. (Photo courtesy ADA-ES)

and in the West, softer subbituminous or lignite coals are the typical choice. The behavior of these coal types varies significantly with regard to mercury emissions: most—more than 60%—of the mercury released from the combustion of eastern coal is in the soluble and more easily captured ionic form, whereas only 20–30% of mercury released from western coal is ionic. Thus, even though eastern coals typically contain one-third more mercury than western types, plants firing western coal generally will require more aggressive approaches to control mercury emissions.

Precombustion cleaning increases the mercury difference between coal types, because eastern coal can be cleaned prior to use whereas western types generally cannot. Cleaning removes noncombustible materials and, for eastern coals, reduces mercury content by about one-third on average. For western coals, various dewatering treatments have been ex-

plored to improve combustion properties; such dewatering appears to also remove mercury—up to 70% in tests—and may become commercial in the future.

Cleaned or not, once coal reaches a power plant, several mercury control strategies are possible. First, the combustion process can be modified to increase the yield of unburned carbon in the fly ash, which can adsorb mercury emissions; the additional carbon may also increase the percentage of ionic mercury. These changes may be accomplished by staging the flow of air or coal in the boiler or by adding halide salts or other treatments to the coal or directly in the boiler.

“Several of our research projects have shown that adding a little halogen to promote oxidation significantly improves short-term mercury capture on western coals,” says Ramsay Chang, EPRI’s technical leader for air emissions. DOE-NETL is following up on these results in 2005

by cofunding longer-term tests of halogen additives at two power plants burning western coals.

Increased yield of ionic mercury or adsorbent carbon ash can also be accomplished by blending different types of coal. In short-term tests at Sunflower Electric's 360-MW Holcomb Station, located near Garden City, Kansas, EPRI researchers found that mixing modest amounts of bituminous coal with the subbituminous Powder River Basin (PRB) coal fired at the plant reduced mercury emissions by up to 80% without any other changes.

"The emissions control equipment at Sunflower's Holcomb Station is typical of many power plants in the West," says EPRI's Specker. "It has exactly the same configuration as most of the new plants being planned that will burn PRB coal. This makes the results particularly significant." Indeed, EPRI recently honored Sunflower Electric with its 2005 Technology Achievement Award for Rural Electric Cooperatives for hosting this work.

Tests at Holcomb Station are part of EPRI's work with DOE-NETL to perform extensive longer-term mercury control technology testing for coal plants in the 2004–2007 timeframe. EPRI is coordinating with the power industry to shape the design and content of the DOE-NETL tests. It's a big job: in addition to government agencies and host Sunflower Electric, the Holcomb test alone involved ADA-ES, Inc., NORIT Americas, Arch Coal, Western Fuels Association, Kansas City Board of Public Utilities, Westar Energy, Empire District Electric Company, Nebraska Public Power District, Kansas City Power and Light, Tri-State Generation & Transmission, Missouri Basin Power Project, Wisconsin Public Service, Associated Electric, Southern Minnesota Municipal Power Agency, the City of Sikeston, TransAlta Utilities, and TransAlta Energy.

Co-Benefit Approaches

The mercury-control potential of combustion modifications at many plants may be limited by the chemistry governing

plant efficiencies, by boiler corrosion from halide salts, or by the economics of coal transport. But "co-benefit" modifications are possible that can boost mercury capture in equipment already installed to control SO₂ and NO_x emissions.

SO₂ is captured by routing flue gas through large liquid-filter flue gas desulfurization (FGD) scrubbers or through spray dryers that work with an injected slurry of a calcium compound. Such SO₂ controls capture nearly all of the ionic mercury emissions but almost no elemental mercury. Consequently, mercury control based on SO₂ controls and combustion modifications work best at plants firing eastern coal. FGD additives are being developed to retain the mercury in the scrubber liquid once it is captured and prevent its re-release in elemental form, which some experiments show may be a concern.

NO_x in flue gas is usually controlled using selective catalytic reduction (SCR) approaches. These catalysts also convert a large fraction of elemental mercury in flue gas to soluble ionic mercury, which can then be captured in FGD scrubbers. Mercury-specific catalysts can be used at plants lacking SCR equipment and at those firing western fuels whose mercury emissions are relatively unaffected by SCR treatment. EPRI and DOE-NETL found catalysts to convert 65–90% of elemental mercury to ionic mercury in the gas streams at a Great River Energy plant and a City Public Service of San Antonio plant, both firing soft western coal; further pilot-scale tests are planned for western and eastern coals in 2005 and 2006.

As more and more SO₂ and NO_x controls are installed to comply with the new Clean Air Interstate Rule, mercury emissions are expected to fall before the cuts required by the Clean Air Mercury Rule phase in. This multi-pollutant co-benefit approach is central to EPA's plan to reduce mercury from power plants. Indeed, a number of vendors are developing integrated environmental control technologies that simultaneously remove mercury,

NO_x, SO₂, and other pollutants, as an economical option for plants installing controls for multiple pollutants at once.

Mercury-Specific Options

Many plants without SO₂ controls will still need to deal with their mercury output, and even those that do have scrubbers in place may need additional mercury controls to meet the final EPA cap. Today's leading mercury-specific approach, adapted from technology devised for solid waste incinerators, is the injection of fine-powder sorbent material—typically activated carbon—into the flue gas flowing from the boiler. A sorbent works by attracting and binding mercury to its surface; the sorbent and mercury together are then captured by a downstream particulate filter such as the electrostatic precipitators (ESPs) fitted at most plants to control fly ash. Short-term tests in 2002 and 2003 indicated high effectiveness—80–90% mercury capture for eastern coals and 60–70% for western coals—but also raised questions of sorbent cost and long-term performance.

To explore possible cost reductions, EPRI and DOE-NETL are cofunding studies of various sorbents. In a four-week test as part of the larger program at Sunflower Electric, a new chemically enhanced sorbent removed more than 90% of the mercury produced at Holcomb Station relatively inexpensively. Without this sorbent, the plant's standard emission controls captured almost no mercury. A combination of conventional activated carbon sorbent and a proprietary additive also proved potentially cost-effective at Holcomb.

"From the perspective of a power producer, this has been a very important test program, and we are quite pleased with the results," said Wayne Penrod, senior manager of environment and production planning at Sunflower Electric. "We were able to determine that there are perhaps three methods from which we can choose in deciding how Sunflower will comply with future mercury reduction requirements."

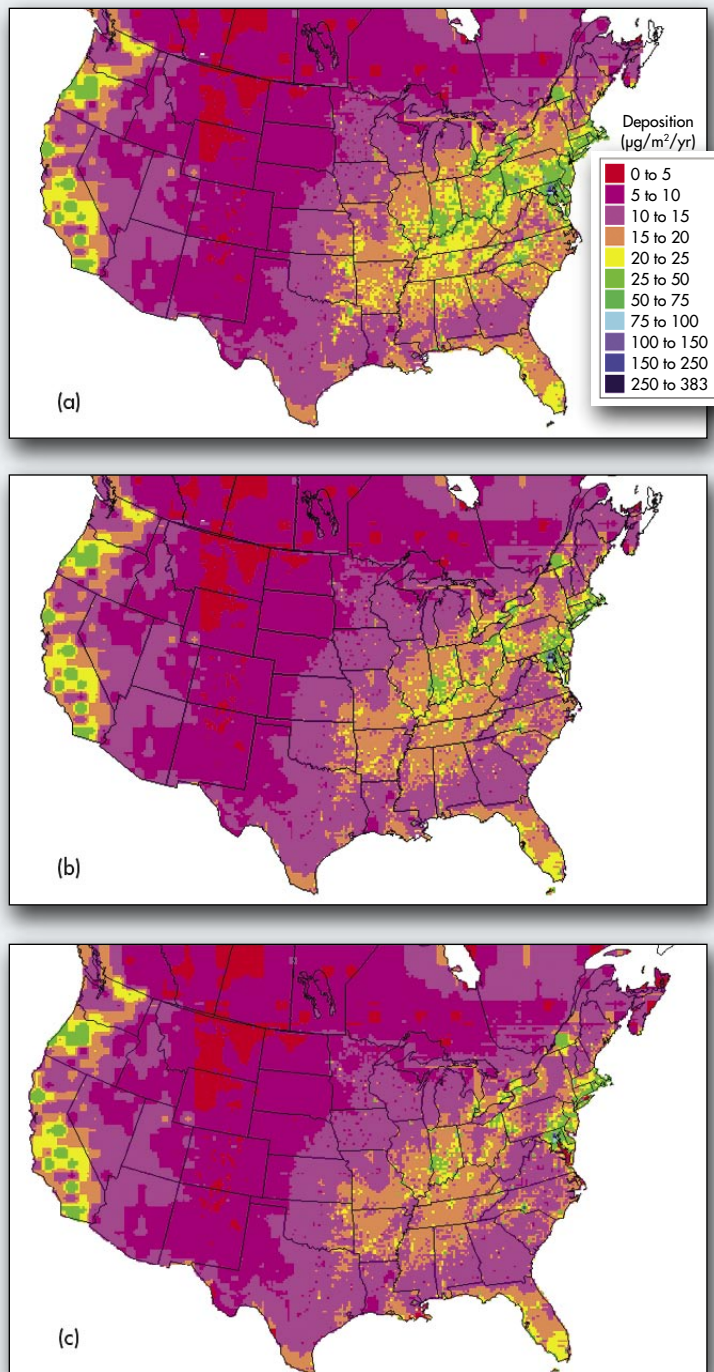
Long-term performance of sorbents will be studied in full-scale power plant tests later in 2005 and in 2006.

EPRI research is also addressing a major problem with using sorbents to control mercury emissions: contamination of fly ash. Currently, a significant amount of fly ash from coal plants is sold to cement makers for use as a concrete additive. This market benefits the environment by reducing CO₂ emissions from cement plants and minimizing landfill. However, conventional sorbents, which are captured along with fly ash, change the properties of the ash and render it unsuitable for use in concrete. Power plant operators who choose sorbents not only stand to lose profitable ash sales, they face large new costs for disposing of millions of tons of ash waste each year.

New TOXECON™ technology patented by EPRI avoids this contamination by separating the capture of fly ash from the collection of mercury-containing sorbent. The process captures mercury as well as or better than conventional sorbent approaches, as demonstrated in 2001–2002 full-scale tests at Alabama Power’s Plant Gaston and in long-term tests conducted in 2004.

TOXECON works by delaying sorbent injection into flue gas until after the fly ash has been collected in a plant’s primary particulate filter; the mercury-laden sorbent is then captured in a secondary filter, or baghouse, installed further downstream. In addition to preserving fly ash for concrete sales, this process requires less sorbent to achieve high levels of mercury capture because the sorbent has greater exposure to mercury in the ash-free gas stream. Consequently, TOXECON is attractive for any power plant that needs to retain ash sales, and it earned runner-up status in the environmental category of the *Wall Street Journal’s* 2004 Technology Innovation Awards.

“We’ve now licensed five companies to use the system, and We Energies has purchased the technology to install in its Presque Isle Station in upper Michigan,”



EPRI global and regional models of mercury deposition (considering all global emission sources) show the expected results of the new Clean Air Mercury Rule. Comparisons of deposition for (a) 2004 and (b) 2020 indicate that the cap-and-trade approach will indeed reduce deposition in the East. However, because mercury emissions from outside the United States are so much higher than domestic emissions, even if U.S. coal-plant contributions (about 40% of U.S. emissions) were completely eliminated (c), overall U.S. deposition would drop by only 9%.

Hot Spots, or What Goes Up Must Come Down—Eventually

The Clean Air Mercury Rule regulates emissions, but the goal is not to improve air quality per se—the highest concentrations of mercury vapor in domestic air run less than one-thirtieth the lowest EPA risk level—but rather to control mercury in fish. The ultimate goal is to protect women and their unborn children by minimizing mercury concentrations in fish that may be eaten by pregnant mothers. Misunderstandings about how coal plant mercury emissions connect to mercury in fish and humans are the sources of much of the controversy over the recent EPA rulemaking.

Most of the major U.S. sources of mercury entering the environment have been controlled by various regulations over the past decades. The major human health concern about mercury pollution is potential neurological damage in fetuses that may result when pregnant women consume certain fish. Bacteria in water transform a fraction of the mercury that enters a lake, a river, or the ocean—whether from human or natural sources—into a compound called monomethylmercury, CH_3Hg^+ , usually referred to simply as “methylmercury.” Fish pick up methylmercury through their food chain and, because it degrades only slowly, larger fish accumulate more and more methylmercury from each smaller fish they eat. Through such bio-magnification, methylmercury concentrations can reach significant levels in top predator fish such as pike, walleye, and swordfish.

Although the level at which methylmercury in fish is risky to fetuses is unknown—no explicit cases have been recorded and studies are obviously impractical—the federal Centers for Disease Control and Prevention has extrapolated from other data to conclude that, at any time, one in six American women of childbearing age has mercury levels in her blood that might put a fetus at risk. At least 43 states issued mercury warnings for lakes and rivers at different times in 2002.

EPA devised the Clean Air Mercury Rule to reduce the impact of mercury on children as much as is practicable. Because mercury deposition levels cannot be known or measured everywhere across the country, rulemaking was informed extensively by computer modeling. Both EPA and EPRI employed state-of-the-art—although slightly different—model sets, both of which are well regarded and give similar results. Each shows that well more than half of the mercury deposited in the United States comes from non-domestic sources (mostly Asia) and that deposition at only a few U.S. locations is dominated by domestic coal plant emissions.

Modelers found—and ground studies confirm—that rather than falling to earth near emission sources, most mercury from coal plants is dispersed throughout the global atmosphere and resides there for up to a year. Eventually the mercury comes down to earth. Because mercury emissions from non-domestic sources are so much higher than those from domestic sources, even if all U.S. coal-plant mercury air pollution were eliminated, overall U.S. mercury deposition would drop by only 9%.

Accordingly, EPRI modeled different mercury control proposals to identify which would provide the maximum benefit at reasonable cost. A proposal to regulate mercury emissions at every plant to a specified emission limit under the Clean Air Act’s Maximum Achievable Control Technology (MACT) provisions was found to reduce average domestic mercury deposition by about 5% at a total cost of about \$10 billion (net present value). By contrast, the cap-and-trade approach, as selected, cuts mercury deposition by 7% at an expected cost of \$2 billion. EPA modeled the cap-and-trade approach as well, with similar results.

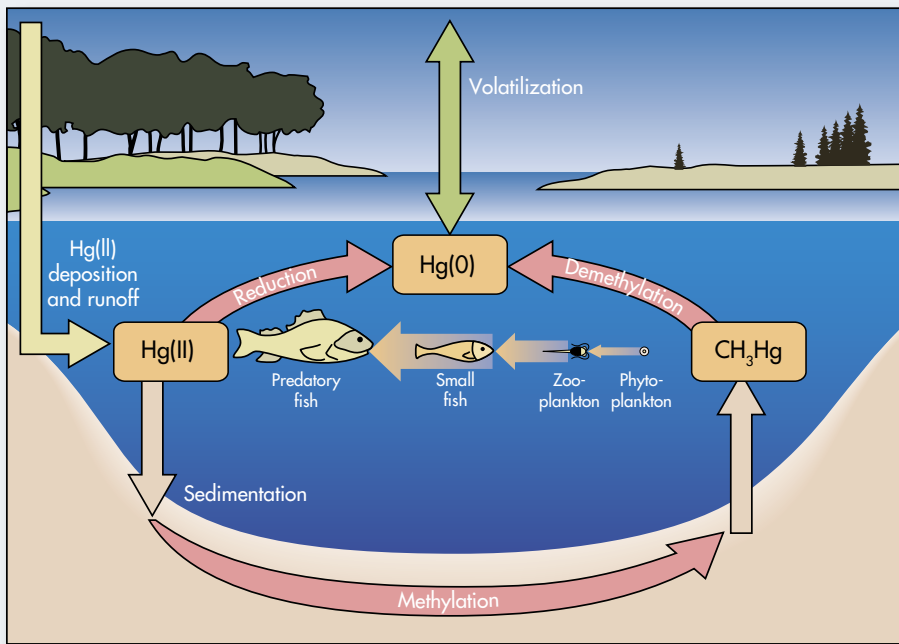
says EPRI’s Offen. The Presque Isle installation, expected to come on-line later in 2005, is cofunded under DOE’s Clean Coal Power Initiative—a program that encourages the use of new technologies by sharing their cost with private industry.

TOXECON is not without competition. New alternative sorbents are being formulated that may not impact fly ash. In early tests these alternatives appear less effective than conventional sorbents, but they may prove less costly than TOXECON. In the

meantime, EPRI is testing a lower-cost variant technology called TOXECON II that avoids the need for a polishing (second) baghouse. In this variant, sorbent injection occurs near the back end of the primary filter, just ahead of the last one or two collection fields but after most of the fly ash has been collected. The final fields then collect the mercury-bearing sorbent separately from the ash, but without a baghouse. Early tests indicate TOXECON II captures 50–70% of mercury

in flue gas from western coal. DOE plans longer-term tests of alternative sorbents and TOXECON II in 2005 and 2006.

The last chance to capture coal plant mercury occurs at the exhaust stack. Here fixed adsorption structures—plates or honeycombs coated with mercury sorbents such as gold or metallized solid polymer electrolytes—can collect much of the mercury remaining in flue gas after other treatments. These technologies, such as EPRI’s Mercury Capture by



Mercury entering lakes—by direct deposition from the atmosphere or via terrestrial runoff—typically includes elemental mercury, $Hg(0)$, and oxidized mercury, $Hg(II)$. An organic form, monomethylmercury, CH_3Hg , may be produced when anaerobic bacteria in the water and sediments methylate oxidized mercury through a metabolic process. Plankton and other organisms bioaccumulate the CH_3Hg , passing it up the food chain to fish, where it may concentrate to levels of concern for human health.

With the cap-and-trade Clean Air Mercury Rule, EPRI finds that the average risk of excess exposure to coal plant mercury for Americans will fall by a factor of 15, from about a 0.6% chance to 0.04%. Reductions will vary across the country, with the smallest changes in low-deposition western states and the greatest reduction in higher-deposition West Virginia. No “hot spots,” with increased mercury deposition, will be created. Although some plants may delay or avoid mercury reductions (because of the availability of emissions credits or because they already

Finally, to address the global nature of mercury control, the United States leads an effort in the United Nations Environment Programme (UNEP) to establish partnerships that would help developing countries reduce mercury emissions. The idea is to leverage technology transfer, resources, expertise, and information exchange to cut mercury use and emissions. This effort accelerates the work of the UNEP mercury program proposed by the United States at the 2003 UNEP Governing Council meeting.

meet future mercury emission requirements), emissions nationally would still decline, as an overall cap on emissions would need to be reached. EPRI modeling finds that none of the 600 power plants with mercury emissions over 100 pounds per year in 2004 would actually increase their emissions. Emissions at only six plants would remain unchanged, and two of these plants already meet the new mercury emission requirements. Additionally, the cost of purchasing credits still motivates power plants to reduce emissions as much as possible. Thus, when the new national cap on mercury emissions is implemented by EPA and the states, a movement away from higher deposition of mercury to waterways would be expected.

EPRI computer analyses of the entire United States show that areas of high mercury deposition are not dominated by electric utility mercury emissions (the largest area, Chesapeake Bay, results from a municipal incinerator). Indeed, EPA analyses show that growth in emissions from domestic non-utility sources will continue to drive deposition changes even following the new power plant rule.

Adsorption Process (MerCAP™), are mostly in early development.

The Final Cost of Control

Today there is no question that coal plant mercury emissions can be captured, but the long-term effectiveness of the different control strategies remains uncertain. Extensive field tests involving U.S. government organizations, EPRI, and the power industry are expected to confirm by the end of the decade that appropriate

approaches can be confidently deployed to the nation’s coal plants to meet the phased emission reductions required by EPA’s mercury rules.

The final cost of the Clean Air Mercury Rule remains largely unknown as well, but EPA projects that the expense to the nation will run some \$2 billion (net present value). For the residential consumer, EPRI estimates this cost will add 0.1–0.3¢/kWh to the 6–8¢/kWh typically paid in the Midwest—an increase of

about 1.5–3.5%. Better estimates await the conclusion of the ongoing power plant test program. “If the results we get at the end of these field tests are consistent with our process understanding, we’ll be in a good position,” says Offen. “If not, we have more work ahead of us.”

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