COVANTA
Powering Today. Protecting Tomorrow

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June 18, 2014

Mr. Anthony Moore, Chairperson
Chester Planning Commission
Chester City Hall
1 Fourth Street
Chester, Pa. 19013

Honorable Mr. Moore and Commission Members:

This is in follow-up to the Chester City Planning Commission Meeting held on June 11, 2014. At that meeting, consideration was given to Covanta's land development review application for construction of an intermodal container building to enable the facility to accept rail transported intermodal containers with waste as an alternative transportation method. The facility is located at 10 Highland Avenue in Chester.

My hope is to address the concerns raised by citizens during the meeting, as well as to convey additional supporting information to the Commission to assist in their ultimate decision. Citizens expressed concerns that there would be increased waste processing at the facility, an associated increase in traffic, and increases in the discharge parameters from the facility. Attachment 1 was prepared specifically to address these issues. Provided within that attachment are the following:

- Condition 8 of Solid Waste Permit number 400593, issued September 7, 2009. That condition defines the receipt parameters associated with the facility. No changes have been requested relative to this condition.
- Typical daily receipts listing for existing permit conditions. This conveys the relative distribution between packers and transfer trailers.
- Conceptual typical daily receipts listing with the addition of the receipt of waste via intermodal containers. As you will note, the intermodal containers that come in effectively replace the transfer trailers on slightly less than a one-for-one basis. This would result in slight increase in daily receipt vehicle movements, but well within previously evaluated vehicle movements. As you will note, packer volume is just under 8%. If any packers were offset, that offset would be on a two-for-one basis. At this time, that is not expected to occur. As mentioned, all traffic would be within the parameters previously evaluated for the facility.
- Pictorial of a transfer trailer and a drop deck trailer containing an intermodal container. This is offered in the hope of conveying the relative difference between the two modalities, despite the fact that each contains essentially the same quantity of waste.

As I believe we conveyed during my testimony at the meeting, the development of our proposed intermodal container scenario was done with active presentation to community members and the Department of Environmental Protection, including the operation of a pilot project during which we invited community members and the DEP to witness those operations. That visitation took place following a Chester Environmental Partnership meeting on October 8, 2013.

At an earlier Chester Environmental Partnership meeting, the same questions were raised with regard to the emissions parameters and health risk parameters associated with the facility. In response to that citizen inquiry during that Chester Environmental Partnership meeting, a letter was prepared to specifically address those questions. That letter and attachments are provided herewith as Attachment 2. I believe that that attachment fully addresses the emissions parameters and health risk concerns which were raised.

While I did not mention this during my testimony, rail transport is generally considered more efficient, from an energy and greenhouse gas perspective, and with fewer accidents per ton/mile. Under this thought process, the proposed rail movements could be viewed as an improvement from a safety and environmental perspective. In addition, though not part of this permitting consideration, providing this infrastructure for handling intermodal containers may improve the likelihood that we are able to bring rail to the facility. Under that scenario, we would see a direct reduction in truck traffic.

Finally, some representations were made regarding a similar project we are doing in Niagara Falls, New York. That project, as in this one, does not involve any changes in waste receipt or in environmental parameters. That project, though, does involve direct rail, so there would a reduction in truck traffic.

Enclosed are sufficient copies for all Commission members, Planning Department officials, and additional copies for concerns citizens. Please feel free to contact me at your convenience should there be any questions regarding this transmittal or to further address any issue or concern.

Thank you very much for the opportunity to present the other day during the Commission meeting and for the opportunity to provide this back up information.

Sincerely,

John G. Waffenschmidt
Vice President,
Environmental Science and Community Affairs

JGW/bjr

cc: William Payne, Chester

Attachment 1 – Supporting materials to respond to citizen concerns on 6/11/14.
Attachment 2 – Letter, JGW to Dr. Strand at Chester Environmental Partnership, 10/30/13 (with supporting materials)

JGW3047

Attachment 1

Delaware Resource Recovery Facility

Waste Receipt Limitations

Typical Receipts and Anticipated Receipts

Vehicle Pictures

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF ENVIRONMENTAL PROTECTION
BUREAU OF WASTE MANAGEMENT

Permit For Solid Waste Disposal and/or Processing Facility FORM NO. 8

Permit No. 400593
Date Issued September 7, 2009
Date Expired September 7, 2019

C. Ash and ferrous waste hauling vehicles, whether entering or exiting the facility, shall adhere to the same schedule as that provided in Condition No. 10 of this permit relating to permitted waste acceptance hours.

7. This permittee shall incinerate municipal waste and Residual Waste in accordance with the maximum municipal waste combustor unit loads (pounds of steam per hour) contained in the facility's Air Quality Permit 23-00004, or any subsequently approved modifications or renewals thereof.

8. The permittee shall accept no more than a maximum of 5,700 tons of waste per day on any given day, Monday through Friday. The permittee shall accept no more than a maximum of 3,000 tons of waste per day on any given Saturday and on the following holidays: Memorial Day, Fourth of July, and Labor Day. In addition, at no time shall the permittee accept more than 26,100 tons of waste per week. For purposes of this condition, a week is defined as Monday through Sunday. A quarterly report shall be submitted to the Department's Southeast Regional Office providing a summary of the total tons of waste accepted at the facility during each day and the total tons of waste accepted during each week of the calendar quarter. Included in the report shall be a listing of each day and the hours during each day that waste was accepted at the facility for the calendar quarter. The report shall be submitted on or before the 20th day of April, July, October, and January for the calendar quarter ending the last day of March, June, September, and December, respectively. The permittee shall also comply with the following:

A. Utilize the approach route to the facility by bringing truck traffic into the site on Harwick Street from 2nd Street instead of utilizing Thurlow Street from 2nd Street. Thurlow Street between 2nd Street and the facility is to be used by truck traffic only when the Harwick Street entrance is blocked due to circumstances beyond the permittee's ability to control. The Department, the City of Chester, and any local neighborhood association which requests notice shall be notified by telephone as soon as the permittee has reason to believe that Harwick Street is or will be blocked.

Delaware Valley Resource Recovery Facility

Daily Waste Receipt Considerations

Typical Existing conditions

192 Transfer trailers @ 21.86 tons/trailer	= 4,197 tons received
38 Packer trucks @ 9.5 tons/packer	= 361 tons received
	4,558 tons received
230 vehicles	

Typical Expected conditions with Intermodal Containers

137 Transfer trailers @ 21.86 tons/trailer	= 2,995 tons received
60 Intermodal Containers @ 20 tons/container	=1,200 tons received
38 Packer trucks @ 9.5 tons/packer	= 361 tons received
	4,556 tons received
235 vehicles	

Note: Waste receipt numbers tend to be higher earlier in the week. Actual daily receipt calculations will vary from the typical conditions listed. Calculations are based on our current understanding/expectations for intermodal containers; actual weights may differ. Actual transfer trailer weights may be lower once intermodal containers are received as some of the displaced customers are believed to be those which bring heavier loads. Information provided for illustrative purposes only.

Open-Top Walking Floor Trailer

Drop Deck Trailer with Intermodal Container

COVANTA
ENERGY
for a cleaner world

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October 30, 2013

Dr. Horace Strand, Chairman
Chester Environmental Partnership
1007 W 7th Street
Chester, PA 19013

Dear Dr. Strand:

During the recent CEP meeting, a question was raised with regard to a comparison of the Delaware Valley facility in Chester (Delco) to the Lancaster County Resource Recovery (Lancaster) facility. The purpose of this letter is to answer that question from both a technology and emissions performance perspective.

Regulatory Background

~~The Delco and Lancaster facilities were permitted at separate times with different permit~~ conditions; however, at this time they are both subject to the same regulatory standards known as Emission Guidelines (40 CFR Part 60, subpart Cb). These USEPA standards include three general sets of parameters for all large municipal waste combustors (MWCs) including: 1) emission limits, 2) operating conditions, and 3) monitoring and reporting requirements.

The emission limits were established by USEPA's Maximum Achievable Control Technology (MACT) floor determination in 1995 that had a compliance milestone of December 2000. At that time, all facilities had to comply with the same stack emission limits with the exception of carbon monoxide and nitrogen oxides, which were based on combustor technology. All facilities also had to comply with USEPA Good Combustor Practices (GCP), a set of three parameters (CO limit, flue gas temperature limit, and steam generation limit) to ensure continuous compliance with stack dioxin limits. Lastly, all facilities are required to continuously monitor stack emissions (CO, NOx, SO2, opacity) and certain operations when an emission could not be reliably and continuously monitored.

Engineered Features

Delco utilizes the O'Connor Rotary Combustor technology which incorporates a rotating drum along with an automatic combustion control system to ensure complete combustion. Each of the six rotary combustors is followed by a semi-dry scrubber and a fabric filter baghouse. A

Attachment 2

continuous emissions monitoring system (CEMS) ensures that the pollution control characteristics of the facility are maintained on an ongoing basis 24 hours a day, 365 days a year. Compliance with the NOx limit is through effective combustion air management and design of the combustion unit.

Lancaster utilizes Martin reverse-reciprocating grate waterwall furnaces along with an automatic combustion control system to ensure complete combustion. Each of the three combustors is followed by a semi-dry scrubber and a fabric filter baghouse. A CEMS ensures that the pollution control characteristics of the facility are maintained on an ongoing basis 24 hours a day, 365 days a year. In addition, the facility utilizes an aqueous ammonia system for the control of nitrogen and carbon for the control of mercury and dioxin.

Modern Energy-from-Waste (EfW) facilities all typically have acid gas scrubbers, fabric filter baghouses, and CEMS. The scrubber/baghouse combination is essentially the workhorse of the emissions control system, with the CEMS as the monitor of that performance. As you will note in the description above, the two facilities utilize different combustion technologies. While these are differences in technology, essentially the same complete combustion occurs.

Emissions Performance

Listed below are the permit limits and emissions performance for both facilities. We utilize a three-year average in order to provide a more accurate gauge of long term performance as opposed to only providing one set of stack test performance numbers. To better enable an understanding of the acronyms used, they are defined at the end of this letter.

Delco				
Reference Information		Emission data		
Emission	Concentration	3 year average	Permit Limit	% Below
Dioxin	ng/dscm@7%O_2	2.49	30	91.69%
Hg	ug/dscm@7%O2	7.23	50	85.54%
PM	mg/dscm@7%O2	1.60	23	93.05%
HCl	ppmdv@7%O2	0.25	25	98.99%
SO_2	ppmdv@7%O2	17.46	29	39.79%
NOx	ppmdv@7%O2	123.59	180	31.34%
Cd	ug/dscm@7%O2	0.61	15.8	96.17%
Pb	ug/dscm@7%O2	2.05	166	98.77%

Lancaster				
Reference Information		**Emission data**		
Emission	**Concentration**	**3 year average**	**Permit Limit**	**% Below**
Dioxin	ng/dscm@7%O2	1.16	30	96.14%
Hg	ug/dscm@7%O2	0.90	50	98.19%
PM	mg/dscm@7%O2	1.48	27	94.54%
HCl	ppmdv@7%O2	2.19	25	91.24%
SO_2	ppmdv@7%O2	2.11	29	92.72%
NOx	ppmdv@7%O2	153.67	180	14.63%
Cd	ug/dscm@7%O2	0.35	40	99.13%
Pb	ug/dscm@7%O2	5.35	400	98.66%

The pollutants listed above include: combustion products (NOx), acid gases (HCl, SO_2), particulate matter (PM), metals (Hg, Cd, and Pb), and complex organics (Dioxins). Both facilities are considered state-of-the-art with excellent compliance with the MACT requirements.

Discussion

As you can see from the results above, both facilities operate at levels below the established permit limitations. Looking at emissions and how they potentially impact health requires more knowledge than just the emissions concentrations. Factored into any health-based consideration are local meteorological conditions, local topography, and local consumption patterns. While US EfW facilities have been extensively studied from a health risk perspective and found to be fully acceptable, perhaps the most succinct review of the technology was conducted by the UK Health Protection Agency (summary attached, full article sent electronically), who concluded in their 2010 report as follows:

> *'While it is not possible to rule out adverse health effects from modern, well regulated municipal waste incinerators with complete certainty, any potential damage to the health of those living close-by is likely to be very small, if detectable. This view is based on detailed assessments of the effects of air pollutants on health and on the fact that modern and well managed waste incinerators make only a very small contribution to local concentrations of air pollutants. The committee on Carcinogenicity of Chemicals in Food, Consumer Products and the Environment has reviewed recent data and has concluded that there is no need to change its previous advice, namely that any potential risk of cancer due to residency near to municipal waste incinerators is exceedingly low and probably not measurable by most modern techniques. Since any possible health effects are likely to be very small, if detectable, studies of public health*

around modern, well managed municipal waste incinerators are not recommended.'

As a company, we have tried to improve our emissions performance across our portfolio. These programs come under the umbrella of our Clean World Initiative (CWI), started six years ago to further reduce our emissions and discharges and to improve our interaction with the outside world. The CWI includes our Rx4Safety program where we offer free disposal to any community in United States for the collection of unwanted pharmaceuticals; I had previously presented to the CEP on this program. Another program, which you assisted us with, is development of our Environmental Justice policy. Both facilities have benefited from the emissions reduction initiatives associated with the CWI. In addition, the Delco facility was identified as an early recipient of an advanced fabric filter bag technology with which we are experimenting. That technology places a membrane on top of the usual felt material; the hope is to get better fine particulate control. In addition, we are experimenting with different pulse systems to further enhance fine particulate capture. As mentioned above, the scrubber/baghouse combination is the work horse of our air pollution control strategy. Our expectation is that by enhancing bag technology we can drive emissions down even further.

Another set of initiatives under the CWI is to clean up the waste stream by eliminating toxics. We are doing that via our mercury programs and our relationship with Call2Recycle which involves the recycling of reusable batteries. Mercury programs that we do locally at Delco include the economic support of the household hazardous waste programs. On a portfolio basis, our mercury program has removed approximately one ton of actual mercury from the waste stream. We had previously supported the mercury export ban associated with the Mercury Export Ban Act of 2008. Our toxicity reduction initiatives of the waste stream, particularly as it relates to mercury, flange up well with worldwide initiatives which seek to eliminate mercury from the products which we use. In that regard, I have attached a series of articles from the journal *Science* on the Minamata Convention, a planetary effort to eliminate mercury from products and to stamp out the remaining anthropogenic sources of those mercury emissions. The relevance of our efforts is that, if there were no mercury in products, there would be less mercury in the waste stream. I say less because it is important to recognize that not all mercury is anthropogenic. Some earlier EPA work suggests that approximately 50% of Mercury emissions are anthropogenic and 50% are biogenic. If you look through the attached literature, it can be inferred that that biogenic component may be slightly higher than 50%.

Summary

Inherent design differences between the combustion units result in slightly different air pollution control equipment matrixes for the two facilities. The Delco facility, which utilizes the O'Connor combustor rotary drum configuration, does not require the addition of NOx control or mercury control to enable it to meet the established MACT limitations. Both facilities are considered state-of-the-art with excellent compliance with the MACT requirements. Health risk reviews of modern EfW facilities conclude that health risks are minimal and efforts by Covanta and others will further reduce the mercury content of the waste stream.

While I believe this letter covers the overall questions that were raised with regard to a comparison of the two facilities, I realize that there may be some questions associated with these data. Should that be the case, I would be happy to discuss this at the next CEP meeting. In addition, I have copied Jim Rebarchak of the PaDEP so that he may be aware of these data and may want to join that conversation. In the meantime if there are any points of clarification or discussions you would like to have in advance of that meeting, please do not hesitate to give me (516-297-1747) or Steve Jenness (301-461-2241) a call. Thank you.

Sincerely,

John G. Waffenschmidt
Vice President
Environmental Science & Community Affairs

cc:	Gregan, T., CVA	Rebarchak, J., PaDEP
	Jenness, S., CVA	Shankar, S., PaDEP
	Partlow, B., CVA	Wright, A. PaDEP

Acronyms

Cd	Cadmium
CEMS	Continuous Emissions Monitoring System
CEP	Chester Environmental Partnership
CWI	Clean World Initiative
Delco	Delaware Valley facility located in Chester, Pa
EfW	Energy-from-Waste
GCP	Good Combustion Practices
HCl	Hydrogen Chloride
Hg	Mercury
CFR	Code of Federal Regulations
MACT	Maximum Achievable Control Technology
mg/dscm@7%O_2	Milligrams per dry standard cubic meter at 7% oxygen
MWC	Municipal Waste Combustor
CO	Carbon Monoxide
NOx	Nitrogen Oxides
ng/dscm@7%O_2	Nanograms per dry standard cubic meter at 7% oxygen
PaDEP	Pennsylvania Department of Environmental Protection
Pb	Lead
PM	Particulate Matter
ppmdv@7%O_2	Parts per million dry volume at 7% oxygen
Rx4Safety	Prescription for Safety
SO_2	Sulfur Dioxide
USEPA	US Environmental Protection Agency

The Impact on Health of Emissions to Air from Municipal Waste Incinerators

Advice from the Health Protection Agency

Prepared by R L Maynard, H Walton, F Pollitt and R Fielder

Summary

The Health Protection Agency has reviewed research undertaken to examine the suggested links between emissions from municipal waste incinerators and effects on health. While it is not possible to rule out adverse health effects from modern, well regulated municipal waste incinerators with complete certainty, any potential damage to the health of those living close-by is likely to be very small, if detectable. This view is based on detailed assessments of the effects of air pollutants on health and on the fact that modern and well managed municipal waste incinerators make only a very small contribution to local concentrations of air pollutants. The Committee on Carcinogenicity of Chemicals in Food, Consumer Products and the Environment has reviewed recent data and has concluded that there is no need to change its previous advice, namely that any potential risk of cancer due to residency near to municipal waste incinerators is exceedingly low and probably not measurable by the most modern techniques. Since any possible health effects are likely to be very small, if detectable, studies of public health around modern, well managed municipal waste incinerators are not recommended.

The Agency's role is to provide expert advice on public health matters to Government, stakeholders and the public. The regulation of municipal waste incinerators is the responsibility of the Environment Agency.

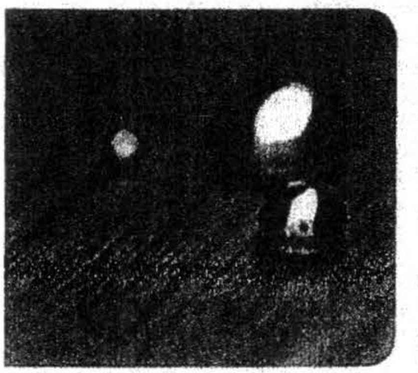
This paper by the Health Protection Agency reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document. It was first published on the HPA website in September 2009 as an HPA position statement and has now been reproduced in this series of advisory documents for convenience of access and citation.

Marcia McNutt is Editor-in-Chief of *Science*.

Mercury and Health

THIS OCTOBER, NATIONS WILL GATHER IN JAPAN TO SIGN THE MINAMATA CONVENTION, A TREATY TO address the toxic effects of mercury in the environment. The agreement will become binding once ratified by at least 50 nations. The convention is timely and welcome in that it places controls and limitations on products, processes, and industries that increase the level of exposure of people and the environment to mercury, a naturally occurring element. Mercury bioaccumulates in the form of methylmercury, a powerful neurotoxin that can affect wildlife, domestic animals, and humans alike. Symptoms of mercury poisoning can range from numbness in the hands and feet and muscle weakness in mild cases, to insanity and death.

This convention is named after the Japanese city where the release of methlymercury in the wastewater from a chemical factory from 1932 to 1968 polluted the local seafood, which then caused severe mercury poisoning in thousands of local residents dependent on that resource. Minamata was a case where science provided the evidence connecting the cause (effluent discharge) with the effect (neurologically diseased patients). Seafloor sediment samples recovered from the bay offshore of Minamata showed that the concentration of methylmercury contamination was highest near the industrial outflow to the ocean and decreased from there. Samples of local seafood and shellfish were laden with mercury. Hair samples from the afflicted population showed highly toxic amounts of the element. Local cats, consumers of the scrap seafood from their owners' tables, were the first to die. Ultimately, the industrial discharge ceased, and the responsible party was ordered to compensate the victims.



Critics of the Minamata Convention believe that it does not go far enough. For example, in 2010 the top two sources of mercury pollution were artisanal gold mining (727 tons) and coal-fired power plants (475 tons).* As many as 15 million adults and children live in communities at risk from mercury pollution from artisanal gold mining, primarily in Africa and South America. Mercury from coal-fired power plants can be transported through the atmosphere far from the source, deposited in aquatic systems, and then converted to methylmercury. The population at risk may have had no voice in the decision to install the coal-fired facility. The treaty stops short of specifying goals or target dates for action plans for reducing mercury release from mining, nor does it require refitting of existing coal-fired power plants to reduce mercury emissions.

One roadblock standing in the way of stronger controls on mercury in the environment, better national action plans, and perhaps even swifter ratification of the Minamata Convention is that many environmental and health aspects of mercury are poorly known,† except in the most acute cases of mercury poisoning. Science can help by linking research on mercury's behavior in the environment (see the Perspective by Krabbenhoft and Sunderland on p. 1457) with studies of its public health impacts. Research teams need to include environmental toxicologists who understand the biochemistry of toxic contaminants, ecologists who trace their bioaccumulation through the food chain, physicians who understand the effects of chronic and acute exposure on long-lived species such as us, and public health specialists who can extract patterns from large populations. What geographic areas are most at risk? Which population demographics are particularly vulnerable? What symptoms should we look for? What other factors might confound their identification? Even at sublethal levels, does exposure to mercury have impacts on the development of young children? Is there a level of mercury consumption that is perfectly safe?

Such investigations cross the boundaries of government agencies and of university schools and departments. Funding the many investigators could be a challenge. But with the number of coal-fired power plants projected to rise globally,‡ tracing the connections between mercury pollution and health must be a priority.

— **Marcia McNutt**

*www.unep.org/PDF/PressReleases/GlobalMercuryAssessment2013.pdf. †For examples of some scientific frontiers, see www.mercury2013.com. ‡www.wri.org/publication/global-coal-risk-assessment.

10.1126/science.1245924

With Pact's Completion, The Real Work Begins

The Minamata Convention on Mercury seeks to curb or end most uses of mercury. It also calls for plenty of research

STOCKHOLM—An elegant crematorium sits in a wooded cemetery here on the edge of the city. It once reduced corpses to ash. But government regulators shut it down not long ago, because its old-fashioned ovens couldn't prevent toxic mercury in the dental fillings of the dead from wafting into the atmosphere, and ultimately falling back to Earth and threatening the living.

Thousands of similar crematoria, and countless other industrial sources of mercury, could eventually face similar regulation as a result of the Minamata Convention on Mercury to be finalized in Japan next month. Years in the making, the agreement calls on signing nations to launch a wide range of initiatives to reduce mercury pollution, which can cause birth defects, brain damage, and disease in humans and other animals. Goals include curbing mercury emissions from coal-fired power plants and industrial facilities, phasing out by 2020 many consumer products that contain mercury, "phasing down" the use of mercury in dental amalgams, and closing all mercury mines within 15 years after the convention takes effect. (Use of existing mercury in research and medicine, however, could continue.)

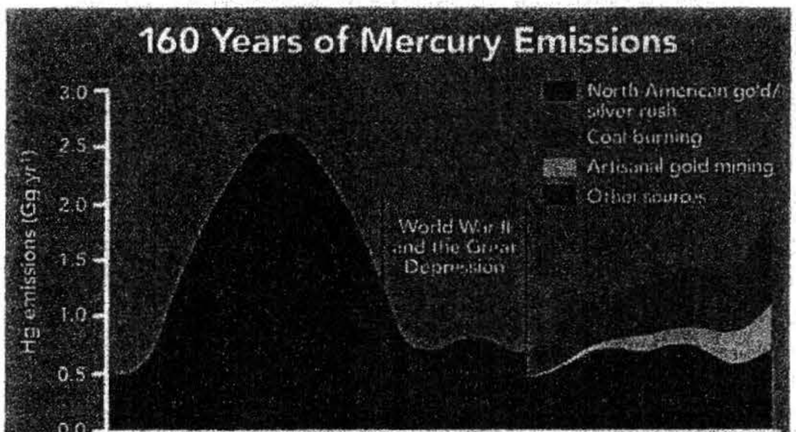
It's an ambitious to-do list, and many of the convention's goals are essentially voluntary, qualified with the phrase "where feasible." But modeling studies suggest that it could, under aggressive regulatory scenarios, help reduce global mercury emissions by 15% to 35% in coming decades.

Beautiful killer. Mercury, here on a gold miner's thumb, can cause brain damage and birth defects.

CREDIT: D. G. STREETS ET AL. ENVIRON. SCI. TECHNOL. 2011, 45, 10485-10491

Still, even some who welcome the convention worry it doesn't go far enough, fast enough. Negotiators stopped short, for instance, of requiring many industrial and power plants to rapidly curb their mercury emissions, giving some a decade or more to act. "That's a lot of mercury" that will be added to the environment in the meantime, says Susan Egan Keane, an environmental analyst at the Natural Resources Defense Council in Washington, D.C. But "the reality is that we wouldn't have had a treaty at all if we didn't have those compromises."

Online
sciencemag.org
Podcast interview with author David Malakoff (http://scim.ag/pod_6153).



Peaks and valleys. Studies suggest mercury emissions surged before and after the chaos of World War II and the Great Depression.

The pact also includes plenty of work for researchers. It tasks nations with beefing up efforts to monitor and tally mercury releases from a slew of sources (see bottom graphic, p. 1445). It also calls for improving efforts to understand mercury's complex chemistry, and how the toxin moves through food chains and ecosystems. And it includes landmark language emphasizing the importance of protecting human health and developing science-based methods of monitoring people at risk of exposure. Such data will be essential to determining whether the convention is achieving its goals—and to enforcing any new mercury controls.

"Under no circumstances do I think this treaty is a silver bullet," says Henrik Selin, a policy researcher at Boston University. But it will become "a focal point" for science and innovation, he predicts.

Trust but verify?

One major task will be clarifying how mercury enters and moves through the environment (see top graphic, p. 1445). Today, researchers estimate that human actions annually dump some 2000 metric tons of the heavy metal into air and water. That's down from an estimated peak of some 2600 metric tons per year in 1890, during a gold and silver mining boom in North America (see graph, below).

But there's plenty of uncertainty in those numbers: The United Nations Environment Programme (UNEP), for instance, recently estimated that annual air emissions could total as little as 1010 metric tons or as much as 4070. Even less certain are the amounts released into water, and the quantities "re-released" into the environment by the vast stores of mercury that have piled up in soils and sediments over the past few centuries. Overall, studies suggest that these "re-emissions" account for about 60% of annual air emissions, double the share contributed by current sources. (Natural sources such as volcanoes and forest fires account for 10%.)

Firming up such figures is a key goal of the new convention, which calls on signers to submit detailed—and accurate—emissions reports. Some existing data gaps might be filled simply by improving tracking of mercury purchases or requiring industries to file more detailed pollution reports. But assembling truly solid

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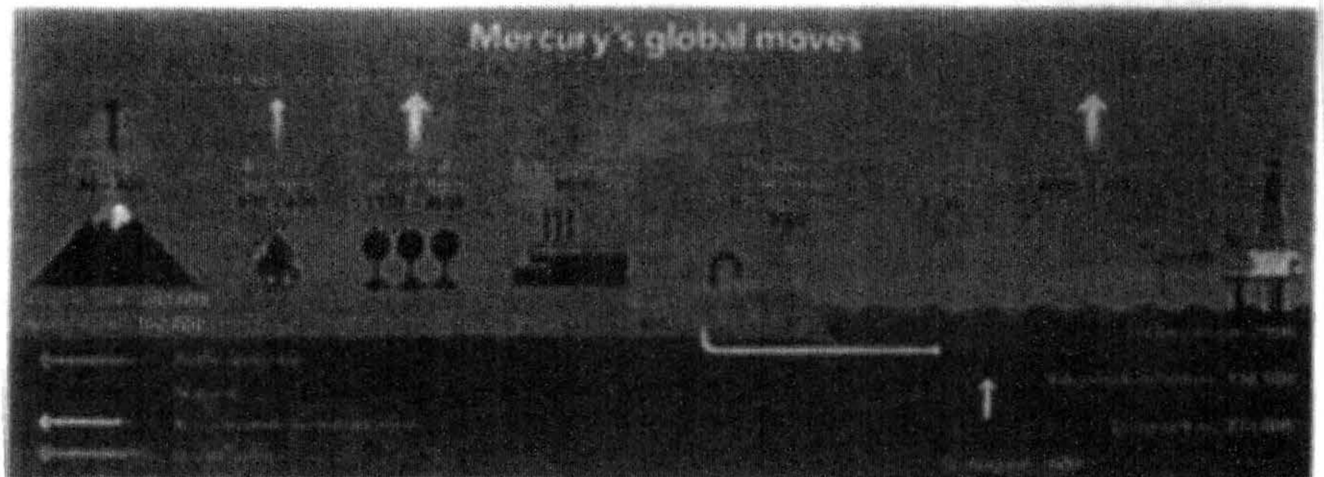
world's existing patchwork of permanent monitoring stations, which feature sensitive instruments able to detect specific mercury compounds. "We have to be able to verify [a country's] emissions inventory … by cross-checking with monitoring and real data," says Nicola Pirrone, director of the Institute of Atmospheric Pollution Research in Rome.

Creating an effective global monitoring system could be a tall task. Although the United States, Canada, and Europe have run relatively robust mercury measurement programs for more than a decade, other regions, especially in the Southern Hemisphere, are barely covered. In one nascent effort to change that, in 2010 Pirrone won support from the European Union to launch a Global Mercury Observation System. In cooperation with others, it has begun installing instruments in places such as Brazil and Argentina. But its future is unclear; the European Union promised just 5 years of funding, and the new instruments are expensive, costing tens of thousands of dollars to build and operate. And although the Minamata Con-vention calls on wealthier nations to help poorer ones boost their data-gathering capabilities, so far there is no concrete funding plan.

Studies have also suggested that some commonly used instruments may not be able to detect important varieties of mercury that form in the atmosphere, giving a misleading picture of emissions and their final resting place. Such findings are a reminder that much of mercury chemistry is still a mystery; scientists don't understand key oxidation processes in the atmosphere, for instance, or how the metal moves and behaves at high altitudes. "If we don't know [such atmospheric chemistry], we don't know anything," says Dan Jaffe, an atmospheric chemist at the University of Washington, Seattle.

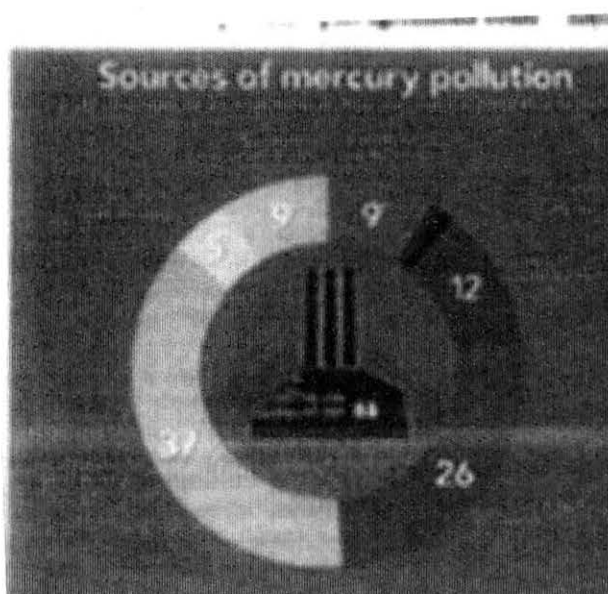


Making tracks. Mercury emissions can move vast distances around the planet in air and water, settling for centuries before being re-emitted to the environment in new forms.

Healthy accord

Although the agreement doesn't spell out exactly how its human health provisions should be implemented—or how the work would be paid for—past agreements could provide a guide. Under the 2001 Stockholm Convention on Persistent Organic Pollutants, for instance, nations ultimately agreed to create coordinated databases that record levels of pesticides and other chemicals in breast milk in order to track infant exposures. Signers of the Minamata Convention could choose to pursue that kind of biomonitoring and reporting infrastructure for mercury, too.

Countries still need to work out what kinds of data to collect, however. Although blood samples can provide extensive information on total mercury exposure, for instance, they can be intrusive to collect and costly to maintain. An alternative might be gathering hair or urine samples, but recent research has shown that each might accumulate a different record of mercury exposure, potentially skewing results. There is also the question of which populations should get priority for biomonitoring—and how to make sure they derive some benefit from research.



Shifting shares. Artisanal gold mining has become the world's leading source of … mercury emissions in recent years.

Such issues are likely to come to the fore as nations begin to implement the Minamata Convention, which will enter into force once 50 nations have ratified it. Then, the clock starts ticking: Nations are supposed to meet for an initial "effectiveness evaluation" within 6 years. By then, researchers hope to be able to report on whether efforts to limit mercury pollution are on track, or are still falling short.

–NAOMI LUBICK AND DAVID MALAKOFF

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Toxic legacy. Decades after mercury pollution ended in the town of Minamata, victims still need help.

MERCURY POLLUTION

In Minamata, Mercury Still Divides

Nearly 60 years after a chemical plant caused one of the world's worst episodes of mercury poisoning, the Japanese town that came to symbolize the metal's threat is still struggling with the aftermath

MINAMATA, JAPAN—Anyone arriving here by train gets the message that this is a company town: The station doors open to a broad tree-lined street that leads directly to the gates of what was once the Shin Nippon Chisso Hiryo chemical plant. The street bisects downtown, mirroring a deeper division in the community that has given its name to the Minamata Convention on Mercury.

Nearly 6 decades after researchers identified the first victims of what came to be called Minamata disease, and 45 years after the government officially recognized that methylmercury discharged from the Chisso plant had caused one of the most notorious pollution disasters of all time, this community and scientists are still split over the calamity, and in some very curious ways. The town hosts both official and "unofficial" Minamata disease museums, for instance. There are also twin disease research institutes, one sponsored by the government, the other by a university.

The two blocks are not—on the surface—antagonistic. "We may have different perspectives, but that doesn't mean we are enemies," says Kunio Endo, a director of the Minamata Disease Center, a citizens' group which operates the unofficial Minamata Disease Museum. But the differences in style and emphasis are clear. The unofficial museum is housed in a tin-roofed shed that sits along a narrow lane high above the town. On a hot, humid day, breezes through open doors provide only occasional relief.

In contrast, the official Minamata Disease Municipal Museum overlooks the bay in a sleek, modern building that is comfortably air-conditioned. And while the municipal museum's slick displays tend to reflect the official line that the Minamata incident is largely resolved, its unofficial counterpart stresses patients' and advocates' view that the tragedy is still unfolding. "There are still many unresolved issues," says Masanori Hanada, a social policy specialist who heads the Open Research Center for Minamata Studies, attached to Kumamoto Gakuen University.

Among them: finding ways to identify patients with less severe mercury poisoning symptoms, and figuring out how low-level or early-life exposure is affecting people as they age. There are also fierce, ongoing battles over who should be counted among the victims of Minamata disease, who could number just a few thousand or up to 100,000—depending on who is counting.

A historic divide

The split in the Minamata community existed even before the disease emerged. The company that ultimately became Chisso Corp. opened a fertilizer plant in the town in 1908 and gradually diversified into a range of chemicals. In 1932, Chisso began making acetaldehyde, used to produce a range of synthetic materials. The production process relied on mercury sulfate as a catalyst, producing an unwanted byproduct known as methylmercury—a potent form of mercury now known to enter the food chain and accumulate in fish and other animals and cause brain damage and birth defects.

As Chisso prospered, Minamata grew, and its economy bifurcated. By the 1950s, roughly one-half of the town's residents depended directly or indirectly on the company for their livelihood. The other half stuck with their traditional livelihoods: fishing and farming. In the spring and summer of 1956, what was first known simply as "a strange disease" started afflicting fishing families in villages scattered around Minamata Bay. Symptoms included numb hands and feet and difficulty walking and talking. Severe cases progressed to convulsions and death. Of 54 patients identified in 1956, 17 died that year, according to the National Institute for Minamata Disease, the "establishment" research institute.

By year's end, Kumamoto University researchers believed the cause was eating local fish and shellfish contaminated with heavy metals. Suspicion focused on the Chisso plant, which discharged its untreated waste directly into waterways. But for several years, Chisso refused to disclose any information; investigators later found that executives covered up in-house research suggesting a link between its wastewater and the illness, and put forward alternative theories.

Residents were divided, either blaming or defending the company. Victims and their families were ostracized; at first, many townspeople feared the illness might be contagious.

In 1959, under pressure from the fishing industry and the national government, Chisso installed a wastewater treatment system. It was of little use, according to a 2011 report prepared by Japan's Ministry of the Environment. "It was later discovered," the report noted, "that the system was not designed to remove mercury and was useless for the removal of methylmercury." In December 1959, Chisso agreed to compensate known victims and fishers, although the company continued to push alternative theories for what was causing the illness, by then dubbed Minamata disease.

For the next 9 years, Chisso and national and local governments considered the case closed. Officials were concerned about the economic impacts of closing or reengineering the plant. So the wastewater taps remained open, and methylmercury continued to accumulate in the tissues of fish and shellfish. The metal also continued concentrating in those who ate seafood, including in the placentas of expectant mothers, exposing the unborn babies to a potent neurotoxin.

Finally, in May 1968, Chisso halted acetaldehyde production, thus ending its use of mercury. (The plant still makes other products.) Later that year, the national government officially acknowledged that Minamata disease was caused by eating seafood contaminated by effluent from the factory. But the statements claimed the outbreak had ended in 1960. And through the early 1970s, the national government continued to play down the threat of eating contaminated seafood from Minamata Bay, ignoring the persistence of mercury in seafloor sediment. Government officials didn't close the bay to fishing until 1975 (lifting the ban in 1997 after massive dredging). Meanwhile, activists started drawing global attention to the growing human toll with dramatic photographs of disfigured, paralyzed victims. "If the national government had taken any measures to stop people from eating fish, we would have had many fewer patients," Endo says.

Who is a patient?

Exactly who those patients are is the subject of much medical and legal dispute, fed by uncertainty about exposure levels and symptoms. The year Chisso stopped using mercury, Minamata patients and advocates formed the Citizens' Council for Minamata Disease Countermeasures to support victims seeking compensation. Since then, there have been 45 years of negotiations, arbitrations, court judgments, bureaucratic diktats, and Cabinet decisions, as well as two laws enacted by the national legislature. The result: a bewildering patchwork of differing classes of victims, levels of compensation, and medical support.

There are, for instance, some 2260 "Certified Minamata Disease Patients" selected by expert panels using strict criteria set by the environment agency in 1977. To qualify, a person must have more than one "severe" symptom, have lived in the most contaminated areas, and been born before 1969. Each has received a lump-sum payment ranging from \$160,000 to \$180,000 plus pensions and medical care.

Under a 1995 national law, another 11,000 patients with less severe abnormalities became eligible for payments of \$26,000 and support for medical expenses. And in 2009, the national legislature created yet another program to support those with even less severe disabilities.

Last April, however, two Supreme Court decisions threw the system into turmoil, overruling one of the expert panels that certifies victims and questioning whether it was scientifically justifiable to require patients to exhibit multiple severe symptoms to qualify. Meanwhile, 65,000 people have applied for compensation under the 2009 law.

Endo says he believes the total number of people afflicted with Minamata disease could be as high as 100,000. One part of the challenge, critics of the current system say, is that screening for signs of methylmercury poisoning was done several years after the crisis and in a piecemeal way. Another is that even people who were exposed to biologically harmful levels may not be aware they have symptoms. "I cannot distinguish by feel whether I'm touching someone's hair or their shirt," says Hajime Sugimoto, a 52-year-old, third-generation Minamata fisherman who lived in Tokyo and worked odd jobs during the ban on fishing. He says he also cannot tell when he has his hands in cold water. But when he was a child, "I thought this was just normal."

To help identify other such "quiet" victims, a team led by Shigeru Takaoka, a physician at the private Kyoritsu Neurology and Rehabilitation Clinic in Minamata, has been doing its own surveys. At the International Conference on Mercury as a Global Pollutant in Edinburgh in July, they reported finding extensive signs of methylmercury poisoning in more than 1000 people living on the coast of the Shiranui Sea, which contains Minamata Bay. "These people are not like the victims seen in the [famous] photographs, but they are Minamata disease patients," Takaoka says.

The long view

More patients could emerge as Minamata's population ages, Takaoka says. His surveys suggest that symptoms may appear or worsen as those exposed get older, but so far there are no large-scale, systematic studies.

Ground zero. Minamata disease was ultimately linked to a chemical plant in the community.

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The slow, late, and cumbersome process of identifying Minamata patients is somewhat ironic, critics note, given that the new convention includes unusual language that commits signers to efforts to understand and monitor the health threats posed by mercury (see story, p. 1443). But it may be in keeping with the conflicted views that many Minamata residents have of the horrendous event that gave the town global recognition. Although the Japanese government successfully lobbied hard to get the convention named for Minamata, Endo says that 90% of residents "are not happy about an incurable disease being named after their hometown."

–DENNIS NORMILE

Exposed. Artisanal miners use mercury to trap flecks of gold, then burn off the toxic metal.

MERCURY POLLUTION

Gold's Dark Side

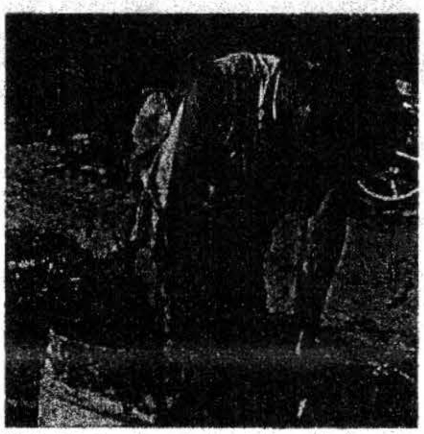
Small-scale artisanal gold mining has become the world's leading source of mercury pollution, poisoning air, rivers, and people

People come to La Rinconada, Peru, for one major reason: gold. There's little comfort, and not much oxygen, to be had in the world's highest city, which climbs windswept slopes at an altitude of more than 5000 meters. But the surrounding Andes mountains are full of the precious metal, and more than 35,000 people have flocked there to mine it, trade it, or otherwise strike it rich.

But if there's gold in the hills, there's a far more sinister element lurking in the city's air, water, and food: mercury.

Endowed with a unique ability to extract gold from low-grade ore, mercury remains the method of choice for artisanal gold miners working near La Rinconada and elsewhere in Latin America, Asia, and Africa. Often very poor, these miners work alone or in small groups, using mercury to separate and bind flecks of gold from soupy slurries of water and sediment. They are outlaws in many countries, eking out a living on the margins of the formal economy. And yet this diffuse industry is now the world's largest mercury polluter, pumping more mercury into the environment than all the world's coal-fired power plants combined. The mining operations typically leave a trail of mercury waste, putting as many as 100 million people at risk of poisoning.

"If you're going to do something about mercury pollution, you have to do something about small-scale mining," says Susan Egan Keane, a senior environmental analyst at the Natural Resources Defense Council (NRDC) in Washington, D.C. She helped governments craft language in the Minamata Convention on Mercury that commits signers to reducing or eliminating mercury use in artisanal mining.



High risk. An artisanal miner in Peru mixes mercury into a barrel of ore and water.

Achieving that goal will not be easy, with gold prices soaring and as many as 15 million miners using an estimated 1600 metric tons of the metal in 2012 alone. Weaning them off mercury will require a blend of economic incentives and practical new technologies, and it could be years before a majority of miners are convinced to adopt them.

It is "an extremely daunting problem," says Luis Fernandez, an ecologist and expert in artisanal gold mining at the Carnegie Institution for Science in Stanford, California. And the stakes are high: "Once areas are contaminated, they are contaminated for a long time."

Why mercury?

Add a palmful of mercury to a slurry of ore and "it serves almost like a sponge," Fernandez says. It soaks up gold that's too diffuse to pan, forming a heavy ball of puttylike amalgam that's easy to pluck out (see graphic, p. 1449). Miners and traders then burn off the mercury, often in an open flame, leaving just the gold.

The process creates ample opportunity for pollution—and exposure. Miners simply dump the mercury-infused slurry, which contaminates rivers. Bacteria in the sediments help transform the inorganic mercury to organic methylmercury, which can be absorbed by phytoplankton and accumulate in fish and other creatures higher on the food chain. People who eat contaminated fish are at risk of neurological damage, autoimmune disease, and devastating birth defects. In a new study, Fernandez found that people in the Peruvian state of Madre de Dios, home to much of the country's artisanal gold mining, have mercury levels in hair averaging 3 parts per million, triple the maximum limit recommended by the U.S. Environmental Protection Agency. "For the most part, these are people who are not miners. These are people who eat fish," Fernandez says. Levels are even higher—more than 5 ppm—in the state's indigenous communities, which rely on local fish for protein.

In mining towns like La Rinconada, the threat is more direct: People are exposed every time they take a breath. As gold shops in the center of town burn the mercury-gold amalgams, mercury vapor wafts into crowded neighborhoods. "In effect, some of these little towns have the equivalent of four, five, 10, 20, coal-fired power plants in the center of them," Fernandez says. Meanwhile, mercury lifted into the upper atmosphere can travel vast distances before falling back to Earth and making its way into the global food web.

Data dearth

Documenting exactly how much mercury miners are using—and exactly how it is affecting people—has been a challenge. Artisanal

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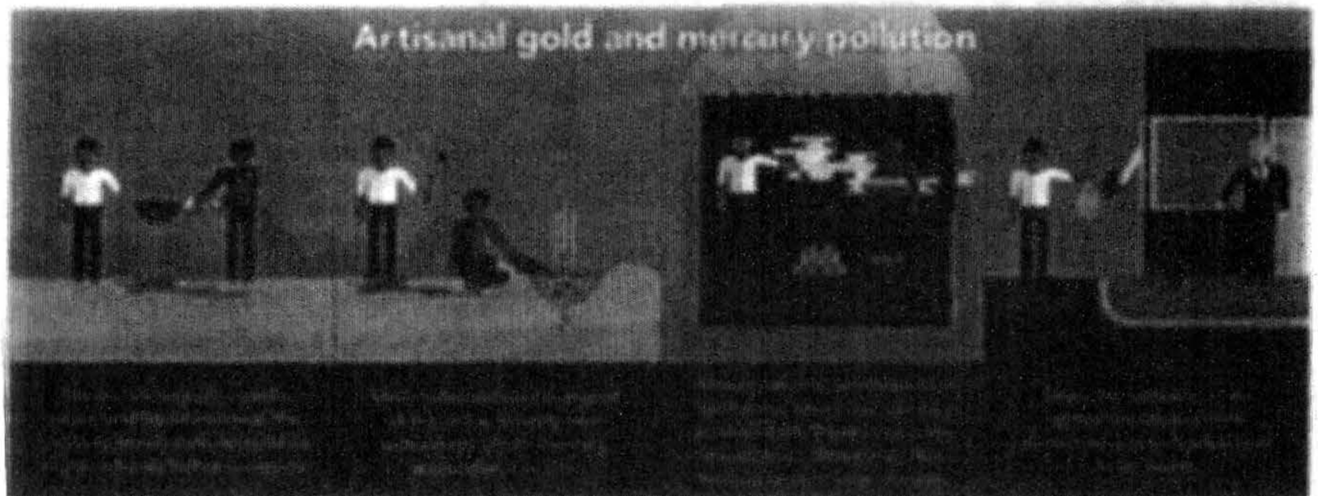

gold mining often takes place in remote areas, and miners can be wary of scientists, whose findings could threaten their livelihoods. "We've been chased out of towns when we've tried to do surveys or a give a talk," Fernandez says. Still, researchers are making progress. The United Nations more than doubled its estimate of mercury emissions from artisanal mining between 2008 and 2013, "mostly due to better reporting," says Kevin Telmer, executive director of the Artisanal Gold Council in Victoria, Canada, which works to reduce mercury use in small-scale mining.

The United Nations may not have the whole picture, however. "The more you look, the more you find," says NRDC's Keane. A 2011 study of the air quality in and around La Rinconada's some 250 gold shops, for instance, concluded that they could be emitting 20 metric tons of mercury per year. That's nearly one-third of Peru's reported annual emissions, suggesting that the official tally is a severe underestimate.

Information on the health effects of artisanal mining is also scarce, because of the challenge of doing long-term studies in poor, remote, and sometimes hostile communities. When Daniel Peplow, an environmental toxicologist at the University of Washington, Seattle, was working with at-risk indigenous communities in Suriname, he recalls that community leaders said: "We're really tired of you people, you scientists, coming here, studying us, taking away information, and not coming back. We're not benefiting from your research." In response, Peplow founded the Suriname Indigenous Health Fund, which helps indigenous communities direct their own research on mercury's impact. Often, he says, they request screening programs to determine who has been exposed, as well as long-term monitoring to reveal whether efforts to reduce mercury exposure are improving health.

Many observers, however, say the world already knows enough to take action. "There's ample information already available that shows that the people in small-scale mining communities are exposed to mercury, which is a well-characterized neurotoxin," Keane argues. The real issue is finding workable ways of getting mercury out of the global gold trade.

Simply banning artisanal mining—or mercury—isn't a realistic option, specialists have concluded. "Making [artisanal mining] illegal hasn't worked," Keane says. It only demonizes miners and drives their activity further underground, cutting off the very resources they need to improve their practices: education, training, and credit. "You cannot deal with someone who officially doesn't exist," says Jacopo Seccatore, a doctoral student in mining engineering at the University of São Paulo in Brazil.

The only winning strategy, Seccatore says, is creating economic incentives to reduce mercury use. "It's all a matter of efficiency. If [miners] get more gold from their ore than they do right now, they will shift immediately to mercury-free technologies." Indeed, mercury amalgamation often "wastes" more gold than alternative methods, some of which are as simple as running slurry through a box lined with a hairy piece of gold-trapping carpet.

The problem, Seccatore says, is that switching to new techniques requires upfront resources that most miners don't have. "They don't have the structure, they don't have the knowledge, and they don't have the money to give up mercury for some safer technology." Plugging those gaps will require transforming artisanal mining into a more formalized industry, argues Marcello Veiga, Seccatore's mentor and a mining engineer at the University of British Columbia in Vancouver, Canada. To that end, Veiga and Seccatore are working with the Ecuadorian government to establish the International Training Centre for Artisanal Miners (ITCAM) in Portovelo. By training miners to use environmentally sound techniques and attract investors with business plans, they hope to "turn every artisanal miner into a responsible, small-scale miner," Seccatore says.

Such economic strategies ring true with the gold council's Telmer. "Health [and] environmental messages will fall on deaf ears and have for 30 years," he says. And Latin America is an attractive place to try experiments like ITCAM, he adds, because many of the region's miners are already organized into cooperatives, unlike in Africa and parts of Asia, where miners usually work alone.

The Minamata Convention could also help create economic incentives for change. It calls for ending the primary mining of mercury within 15 years once 50 nations have ratified it, ultimately limiting supplies and likely raising prices. "Inevitably there will be a squeeze on mercury," Telmer predicts. That could help make alternative techniques more attractive to miners, and even encourage gold shops to capture, recycle, and resell mercury they now burn.

Still, specialists fear that the convention may be too little, too late to erase gold's toxic legacy. Ultimately, the agreement may "do a great job stemming the flow of mercury" from artisanal mining and other sources, Peplow says. But the vast quantities of mercury already dumped by artisanal mining will persist in ecosystems for hundreds of years, he notes, and "there's no going back."

–LIZZIE WADE

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ENVIRONMENTAL SCIENCE

Global Change and Mercury

David P. Krabbenhoft[1] and Elsie M. Sunderland[2]

Mercury concentrations in the atmosphere and oceans are affected not only by anthropogenic emissions but also by climate and ecosystem change.

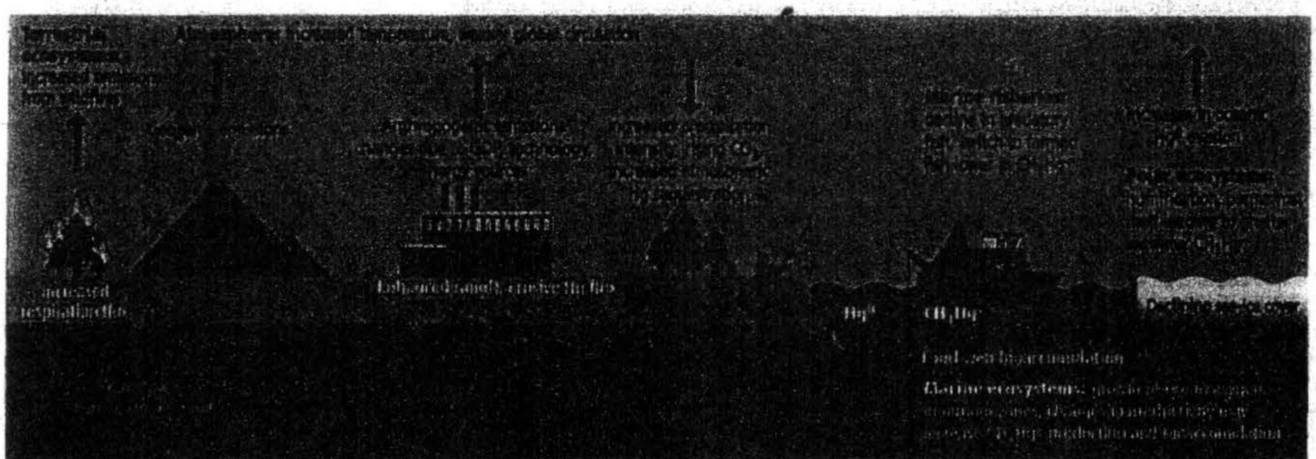
More than 140 nations recently agreed to a legally binding treaty on reductions in human uses and releases of mercury that will be signed in October of this year. This follows the 2011 rule in the United States that for the first time regulates mercury emissions from electricity-generating utilities. Several decades of scientific research preceded these important regulations. However, the impacts of global change on environmental mercury concentrations and human exposures remain a major uncertainty affecting the potential effectiveness of regulatory activities.

Mercury is naturally abundant in heavy-metal–rich geologic deposits and coal. Since antiquity, humans have intentionally (mining) and unintentionally (fossil-fuel combustion) liberated mercury from these stable long-lived reservoirs (*1*). Global mercury releases increased steeply during the 16th-century silver production rush in Spanish America, and again during the late–19th-century gold rush in North America (*2*). Over the past century, anthropogenic mercury releases have been dominated by atmospheric emissions from fossil-fuel combustion, particularly coal-fired power plants (*2*). Artisanal and small-scale gold mining in developing countries has recently replaced coal combustion as the largest anthropogenic mercury emission source globally (*3*). This often unrecognized industry employs at least 10 to 15 million people globally and poses severe health risks to the miners due to inhalation of concentrated elemental mercury during gold recovery (*3*).

Most mercury released to the atmosphere is in the gaseous elemental (Hg^0) form, which has a long atmospheric lifetime (6 to 12 months), allowing hemispheric-to-global mixing and transport before deposition. Elemental mercury reacts with atmospheric oxidants such as bromine to form the highly water-soluble divalent mercury species (Hg^{II}) that is rapidly deposited to terrestrial and aquatic ecosystems. Some of this mercury is reduced back to Hg^0 and reemitted to the atmosphere; the remainder cycles through soils and the oceans over time scales ranging from decades to many centuries until it is resequestered in the lithosphere (*4*).

Sedimentary records of historical pollution provide evidence of a three- to fivefold increase in global atmospheric concentrations since the mid-1800s (*5*). Assessments that account for releases since antiquity suggest that humans have increased background atmospheric concentrations and deposition by a factor of 7 to 10 worldwide (*1*, *4*). Modeling and observations also provide evidence of human-driven changes in seawater mercury concentrations (*4*, *6*). A shift in global anthropogenic mercury releases from North America and Europe to Asia in recent years can be linked to decadal-scale decreases in mercury concentrations in the Atlantic Ocean and contrasting increases in the Pacific Ocean (*6*).

Methylation of inorganic mercury in wetlands, lakes, rivers, and seawater leads to the formation of methylmercury, a potent neurotoxin. Methylmercury is the only species of mercury to become concentrated with each successive level in the food chain, reaching levels in predatory fish that are about a million times higher than in seawater (*6*, *7*). Fish are the main methylmercury exposure source for most wildlife and humans. Experimental data show that methylation of inorganic mercury responds proportionally to changes in mercury inputs (*8*), suggesting that reductions in human and wildlife exposures are achievable with declines in environmental releases over the long-term (*6*, *7*). Epidemiological studies show long-term neurocognitive deficits in children exposed to methylmercury and some evidence for impaired cardiovascular health in adults (*9*).



How mercury cycles through the environment. Global change interacts directly and indirectly with mercury cycling. Numerous physical, chemical, and anthropogenic drivers will affect future mercury conditions in the atmosphere, terrestrial systems, and oceans.

Currently, human activities result in mercury emissions of ~2000 metric tons per year. Global anthropogenic emissions scenarios for 2050 range from a best-case decrease from present levels to 800 metric tons per year (driven by mercury-specific control technology and co-benefits from climate mitigation strategies) to an increase to 3400 metric tons per year under a business-as-usual scenario (*10*, *11*). Present-day human sources consti-

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tute ~30% of atmospheric emissions each year, with the remainder attributed to terrestrial and oceanic emissions that originate from legacy anthropogenic and natural mercury sources (3). Terrestrial and oceanic mercury reservoirs will continue to grow and release more mercury under all but the most stringent emissions controls scenarios, meaning that aggressive emissions reductions are required to stabilize background concentrations in the atmosphere and global oceans (4). However, future emissions trajectories are highly uncertain and depend on changes both in the global economy and in technology penetration.

Global biogeochemical cycling of mercury will also be affected by rapid climate change (see the figure). Weaker global circulation and elevated temperatures will affect atmospheric oxidation rates and patterns of deposition globally. Increased precipitation intensity and incidence of extreme storm events are likely to lead to increased mercury inputs to aquatic systems through direct deposition, runoff, and erosion. Terrestrial soils are the largest global mercury reservoirs (4) and atmospheric mercury sequestration will likely increase in areas where ecosystem primary productivity is stimulated by increases in precipitation and elevated atmospheric CO_2 (12).

Furthermore, increases in the frequency, scale, and intensity of wildfires are likely to mobilize vast stores of mercury in terrestrial soils (4). Changes in ocean circulation, productivity, and growth of oxygen minimum zones will likely alter rates and patterns of methylmercury formation in seawater (6). In polar regions, higher temperatures and declining sea ice could enhance oceanic mercury losses through elevated evasion of Hg^0. However, changes in primary productivity and species composition in Arctic ice-free waters have also been associated with an increase in biological mercury concentrations due to differences in feeding preferences (13). Many studies have suggested that climate change will exacerbate methylmercury production and bioaccumulation in aquatic ecosystems, but improved understanding of impacts on global mercury biogeochemistry is necessary for anticipating future human and wildlife exposures and risks.

Mercury cycling and bioaccumulation is also affected by other human-driven changes (see the figure). For example, increased ozone concentrations since preindustrial times are thought to have increased the residence time of mercury in the atmosphere by 66% through interactions with bromine (4). This change, coupled with greater emissions, has promoted an overall increase in the worldwide distribution and accumulation of anthropogenic mercury. Widespread nutrient enrichment of coastal ecosystems is likely to increase methylmercury formation in many ecosystems (6). Increasing consumption of lower–mercury containing fish from aquaculture (particularly in China) and fishing pressure that has decreased the size and trophic level of fish consumed in many regions, have partially offset increases due to rising pollution levels.

The links between environmental mercury cycling and major global change drivers (warming, hydrology, and emission controls) are reasonably understood. However, it remains challenging to forecast a future environment driven by multiple synergistic and antagonistic drivers operating simultaneously. New and rapidly developing scientific tools such as the application of high-resolution mass spectroscopy to fingerprint sources and key processes (14) and genetic markers for the capacity to methylate mercury (15) will help to improve understanding of the cycling and health impacts of environmental mercury.

References

1. O. Serrano, A. Martinez-Cortizas, M. A. Mateo, H. Biester, R. Bindler, *Global Biogeochem. Cycles* 27, 21 (2013).
2. D. G. Streets *et al.*, *Environ. Sci. Technol.* 45, 10485 (2011).
3. U.N. Environment Programme, *Global Mercury Assessment 2013: Sources, Emissions, Releases and Environmental Transport* (UNEP Chemicals Branch, Geneva, Switzerland, 2013).
4. H. M. Amos, D. J. Jacob, D. G. Streets, E. M. Sunderland, *Global Biogeochem. Cycles* 27, 410 (2013).
5. W. F. Fitzgerald, D. R. Engstrom, R. P. Mason, E. A. Nater, *Environ. Sci. Technol.* 32, 1 (1998).
6. R. P. Mason *et al.*, *Environ. Res.* 119, 101 (2012).
7. J. M. Benoit, C. C. Gilmour, A. Heyes, R. P. Mason, C. Miller, *ACS Symp. Ser.* 835, 262 (2003).
8. R. C. Harris *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* 104, 16586 (2007).
9. M. R. Karagas *et al.*, *Environ. Health Perspect.* 120, 799 (2012).
10. P. Rafaj, I. Bertok, J. Cofala, W. Schopp, *Atmos. Environ.* 79, 472 (2013).
11. D. G. Streets, Q. Zhang, Y. Wu, *Environ. Sci. Technol.* 43, 2983 (2009).
12. O. Hararuk, D. Obrist, Y. Luo, *Biogeosciences* 10, 2393 (2013).
13. G. A. Stern *et al.*, *Sci. Total Environ.* 414, 22 (2012).
14. J. D. Blum *et al.*, *Nat. Geosci.* 10.1038/ngeo1918 (2013).
15. J. M. Parks *et al.*, *Science* 339, 1332 (2013).

10.1126/science.1242838

MATERIALS SCIENCE

A Coat of Many Functions

Dmitry Shchukin[1] and Helmuth Möhwald[2]

Smart coatings are designed to be sensitive to various external and internal stimuli, thereby enhancing the surface functionality of materials.

The past decade has seen great interest in the development of smart materials with autonomic functionalities. Among them smart coatings have a special niche, filling the position at the interface between bulk solid substrate and liquid or gaseous external environment. This makes them uniquely well suited for such applications as corrosion protection, detection and delivery of bioactive species, and antifouling. They can provide either autonomic response to fluctuations and variations of the coating integrity (disruption, melting) or stimulated response to changes in the external environment (magnetic or electromagnetic fields). The response action depends on the functionalities that the coatings attain during their preparation. The main challenges are to introduce these improvements, maintain them through all manufacturing steps and material life cycle, and use them efficiently when demanded.

The development of smart coatings possessing rapid or sustained feedback activity in response to external impacts will be an enabling technology for the fabrication of high-tech products with multifunctional surfaces. In general, the coatings combine passive properties inherited from classical coating design (barrier, color, adhesion) and engineered active parts, which are sensitive to instant or gradual impacts occurring either in the coating matrix (pH changes, cracks) or in the environment surrounding the coating (light, temperature, humidity). After exposure to certain impact(s), the active part of the smart coatings responds in order to restore the coating functionality, thus reducing the negative effect of the impact on the coating (self-healing concept) or launching additional properties of the coating interface (bioactivity, detection). The coatings should also have several passive and active functionalities (e.g., antireflection, antifungal, anticorrosion) exhibiting synergistic effects, thus

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