The Rise and Fall of Mercury: Converting a Resource to Refuse After 500 Years of Mining and Pollution

LARS D. HYLANDER
Department of Limnology, Evolutionary Biology Centre, Uppsala University, Norbyvägen 20, S-752 36, Uppsala, Sweden

MARKUS MEILI
Stockholm University, Inst. of Appl. Environ. Research (ITM), S-106 91 Stockholm, Sweden

The link of mercury (Hg) pollution to Hg mining is rarely made, although Hg primary production presently is as large as global Hg emissions from coal combustion. Here we present historical comparisons on global, continental and national scales, covering up to five centuries of Hg production and consumption. Nearly half of the historical consumption has been pre-industrial, notably for silver and gold mining by amalgamation. More than half has been mined in Europe and one quarter in the Americas. Four economic periods with different control of global Hg price and production were discerned: The Hg price rose sharply after 1830 when Spain no longer controlled the Hg market and when consumption started to shift to gold mining in North America and later on industrial uses. In the 1970’s, however, the price as well as quantities consumed plunged as a result of rising health and environmental concerns. In Sweden, per-capita consumption has recently dropped below pre-industrial levels, exemplifying a successful implementation of environmental policy. The chlor-alkali industry is still the globally dominating Hg consumer, and large stocks to be decommissioned in industrialized countries need political guidance to avoid transfer of Hg and related risks to other countries, a potential transfer to small-scale miners favoured by low Hg prices.
KEY WORDS: mercury production, mercury consumption and consumption patterns in America and Europe, mercury price development, mercury waste, final deposition

I. INTRODUCTION

For millennia, mercury (Hg) has been considered a valuable natural resource with a wide range of applications, although the toxicity of elemental Hg was reported already by Pliny the Elder (dead 79 A.C.) and the toxicity of Hg salts was demonstrated by the “mad hatters” making felt hats from furs treated with Hg (as nitrate).20 Health concern was until a few decades ago focused on occupational exposure, e.g. in mines.85 Meanwhile, Hg was used in a wide range of fields such as medicine and technology with few or no restrictions until the last decades of the 20th century. By this time, severe intoxications of people by organic Hg compounds in Iraq, Japan, and the USA was observed, and the public in several industrialized countries forced industry and authorities to recognize the toxicity of Hg and Hg compounds.6,42,87,112,114 Wild life mortality of seed-eating birds and birds of prey caused by seed dressed with Hg compounds,103,122 alerted the Swedes and Finns in the 1960’ies about the risks of using Hg and also initiated studies revealing alarmingly high Hg content in fish caught close to paper and chlor-alkali industries.102 Acquired knowledge about environmental transformations of inorganic Hg to far more toxic organic forms along initially largely unknown transfer pathways focused the attention on the large quantities of Hg used in paper and chlor-alkali plants.89 Swedish authorities were first to act and enforced legislation on the use of Hg in Sweden, to avoid a tragedy such as that in Minamata, Japan.89,112,114 Consequently, seed dressing with methyl-Hg was prohibited in 1966, and Hg was banned from all pesticides in 1988.96,97 Total emissions of Hg from Swedish chlor-alkali plants to air and waters were reduced from more than 30 t per year in the 1950’s and 1960’s to less than 0.1 t in 2000.26,97 Sale of clinical thermometers containing Hg is prohibited since 1992, and since 1993, practically all manufacturing and sale of thermometers, electrical switches, batteries, and other electrical appliances containing Hg is prohibited.108 At present, Hg is still used in fluorescent tubes and energy saving lamps (proposed to be replaced by Hg-free luminous cathode lamps54 and low energy diodes, LED), Hg-cells (expected to be converted to a Hg-free process before 2010)104 in two of originally ten chlor-alkali plants with Hg-cells, and dental amalgams, occasionally still inserted in persons above 20 years of age.109

In many other countries, Hg is still widely used in industry and society, often unregulated e.g. as an amalgamating agent for gold extraction (UNEP).116 Mercury used has originally been extracted from mines. This Hg has caused anthropogenic emissions for more than two millennia,2,20 and
has contributed significantly to elevated atmospheric Hg deposition rates, together with the more recent combustion of fossil fuels. Atmospheric Hg deposition rates have according to Bergan et al.\textsuperscript{9} increased by 1.5–3 times globally and up to 10 times in Europe, North America, and Southeastern China since onset of industrialization, while Shotyk et al.\textsuperscript{100} and Roos-Barraclough et al.\textsuperscript{91} observed even larger increases since pre-industrial times in deposition rates over mires in Denmark, Greenland, and Switzerland. Also Lamborg et al.\textsuperscript{50} concluded that presently the global anthropogenic contribution is twice as large as natural Hg emissions, and the anthropogenic contribution to global Hg pollution has been confirmed by recent analyses of Hg in dated ice and sediment cores.\textsuperscript{12,21,98}

Globally, several emission inventories have recently been compiled based on measured Hg emissions from large point sources such as chlor-alkali plants and other industries using Hg, waste incineration plants, metallurgical plants, and coal combustion utilities, or based on estimated regional combustion rates of fossil fuels and various types of waste and their measured or estimated Hg content.\textsuperscript{81,84} Diffuse emissions of Hg to air and water are often missing or coarsely estimated from population densities.\textsuperscript{46} Emissions from waste disposal are uncertain.\textsuperscript{82} Pacyna and Pacyna\textsuperscript{81} reported 111 t of Hg emissions from global waste incineration in 1995. However, this is stated by the authors to be grossly underestimated and to be multiplied by a factor up to five, since only few countries report quantities of waste incinerated, and even fewer actually measure Hg emissions from waste incinerators. Even less is known about Hg emissions to air and water from wastes disposed in landfills, from which atmospheric emissions are enhanced by intentional or unintentional open fires.\textsuperscript{45,55} Potential emissions are large considering the large amount of Hg yearly transferred into wastes, in the EU alone estimated to at least 990 t per year but, due to missing data, more probably 2000–4000 t per year.\textsuperscript{73}

Even complete emission inventories have the limitation that they do not account for the potential emissions in the future from waste generated or from Hg stocks after that a production process using Hg has ceased, e.g. the chlor-alkali production with Hg cells. In environmental assessments, the emission potential of Hg stocks in a shorter or longer time perspective is occasionally considered,\textsuperscript{4} but is generally ignored.\textsuperscript{28} A valuable help for estimating future direct and indirect emissions of Hg is to complement emission inventories with the best possible records of Hg primary production and consumption patterns, preferably with regional and annual resolution. Such records will not only reveal quantities of Hg produced, but also its geographic destination and potential use, which is valuable information when tracking Hg stocks in the technosphere/society in efforts to reduce their potential effects on human and environmental health.

Long production records of primary Hg are comparably easy to compile, since production has been dominated by a few sites in the European region.
with the largest geological reserves of Hg, and since extraction of Hg has been carefully recorded for centuries due to the exclusiveness of Hg in ancient times. Together with the Spanish monopoly for several centuries, this has contributed to a good documentation of metallic Hg production in Europe and America already since the 16th century, whereas production figures for Asia, the former USSR countries, and Africa are still incomplete. Consumption data of Hg are less accurate than production data because of the widespread use of Hg in practically all countries of the world in multiple uses, often without any registration or documentation. In addition, the stock of Hg in society has increased because market forces have been set aside by public subsidies.

A historic perspective on Hg mining and detailed use patterns can lead to a better understanding of the present and future fate of Hg. Therefore we made an attempt of compiling all available data on both primary production and consumption of Hg with national-regional and annual-decadal resolution for the past five centuries, as well as associated consumption patterns. Sweden is here taken as an example of a country without any Hg mine and having made the transition from consuming large Hg quantities to phasing out practically all Hg use within only four decades. The USA is an example of a former producer of Hg with a large industrial activity based on Hg, thereby largely influencing the international Hg market. Further, we compiled relationships between price and quantities (production as well as consumption), since such knowledge is valuable for evaluating and forecasting effects of market forces and political decisions, historically and in the future. Here, a compilation of data covering several centuries is presented, i) to quantify the role of European and American Hg production in global Hg production; ii) to present the drastic changes in Hg consumption patterns in Sweden for comparison with those in regions with other socio-economic conditions and diverging per-capita Hg consumption; and iii) to relate historic and recent patterns of Hg production and consumption to not only environmental but also economic considerations.

II. MATERIALS AND METHODS

Data on mined quantities of Hg were compiled country by country from statistical yearbooks, scientific articles and other sources. Practically all North American production and consumption and a large part of global production during the past 150 years were reported in Mineral Resources of the United States (1883 to 1934), USGS Minerals Yearbook (1943 to 2001), and USGS Mineral Commodity Summaries, Mercury (1995 to 2001). These data were compared and complemented by data from Metallgesellschaft and other sources. Details are available elsewhere. The aim was to
include all primary (virgin) production including byproduction from mining of other metals, but to exclude secondary production from metal recycling, flue gas cleaning, etc. Data originally reported in flasks (generally à 34.507 kg, rarely à 34.473 kg) and in quintals (à 46.0095 kg) were transformed to metric tons (t) throughout.

American Hg consumption patterns are compared with those in Europe, where data from Sweden are most detailed. Consumption is defined as industrial consumption and consumption of metallic Hg for amalgamation in gold and silver mining and other uses. Accordingly, Hg consumed in products is registered in the country of production and not in the country of final consumption. Although best available data sources were used, data were incomplete, especially from the 19th and the first half of the 20th century. For example, data on Hg used for production of explosives in Sweden were missing and have been collected from rolls on production available for some years at two factories and otherwise by calculating fulminate content of estimated quantities of percussion and blasting caps produced.

Consumption of Hg by Swedish chlor-alkali plants is based on a detailed inventory of emissions. Mercury initially acquired at the start-up of the plants was not included and has here been estimated to 1.8 t Hg per 1000 t of annual chlorine production capacity. After closing of Hg cells at eight chlor-alkali plants in the 1960's–1990's, Hg was either transferred to cells still in operation or sold on the market, where most of it was exported and subsequently officially registered. This Hg has reduced apparent consumption based on trade statistics, while Hg reused in chlor-alkali plants was not registered in official trade statistics, but has certainly also contributed to reduce registered consumption.

Consumption of Hg for production of pesticides and antifouling paints in Sweden has earlier been reported for longer periods, while data on Hg consumed by industries producing electric devices and measuring and control instruments was only reported for 1976. Mercury consumption for this sector during other years was estimated by scaling production statistics since 1858 with unit production in 1976. This Hg consumption estimate was consistent with the Hg net import to Sweden after subtraction of Hg consumed by other sectors.

Consumption pattern in the USA is presented from 1850. Pre 1940 data were scarce but followed regular trends, at least during the 20th centuries, and were estimated either by interpolation or from notes and text accompanying the tables. Consumption data for Japan and European countries other than Sweden were used for comparisons referring to the period of maximal Hg consumption in the middle of the 20th century. Since there are no complete records on global Hg consumption, global net consumption throughout the studied five-century period was assumed to be equal to the contemporaneous global production of primary Hg, because there have been no major stockpiles of Hg extending over more than a few years in the
market economies, except for the US National Defense Stockpile established at the end of World War I. This stockpile is presently holding 4,435 t, but has been built up gradually with a limited impact on the Hg market before part of it was sold out a decade ago. Population data used to calculate per-capita consumption were obtained from statistics of the United Nations, USA and Sweden.

Running Hg prices were available for Almadén (1540–1642), London (1850–1893 and from 1957), and the main shipping ports of Hg in the Americas; Mexico City (1565–1849), San Francisco (1850–1905), and New York (1906–2000). The Hg prices in New York were about 10\% (0.11 US$ kg\(^{-1}\)) higher than in San Francisco during a few years with parallel notations. Prices at both European and American ports are here given in US$ to be comparable. Since the Spanish “Peso” silver coin was the template for the USA Silver Dollar with equal value, the Hispano-American and European price series in pesos were here converted to US$ on a 1:1 basis.

All price series were index-corrected using various indices. First, index-corrected Hg prices from 1910 to present were obtained from Roskill’s Metals Databook 2000. The US Consumer Price Index was used to extend the series between 1820 and 1909. For further extension into the initial exploitation of colonial resources, an average inflation rate of 1\% per year 1540–1550 and 1.5\% per year 1551–1600 was adopted from Hamilton. For the period 1601–1819, inflation was assumed negligible because commodity prices peaked in Spain at the beginning of the 17th century, and because the increase in Gross National Product was only 0.2\% per year in the Americas. Furthermore, currencies were at that time based on weight in silver and gold and more stable than in recent decades.

III. RESULTS AND DISCUSSION

A. Primary Production

Roughly half of the registered Hg production has been extracted in Europe (Figure 1), where Spanish mines alone have contributed one third of globally mined Hg. About one forth has been mined in the Americas, and most of the remaining part of registered, historical Hg production originates in Asia, mainly Kyrgyzstan, other countries of the former USSR, and China. However, the Asian figures may be largely underestimated, because of large gaps in the historical records and registered figures often representing exported quantities, not including domestic consumption in the producer countries. While production has changed dramatically over time and among mines, the global production of primary Hg has always been dominant in the region of the mercuriferous belt between the western Mediterranean and central Asia, but appears currently to be shifting to the east.
The Rise and Fall of Mercury

FIGURE 1. Global, historical primary production of Hg, and the total contribution from Europe and the Americas (area stacked above line for Europe).

Since 1970, the recorded production of primary Hg has been reduced by almost an order of magnitude to around 2 000 t in the year 2000. This is still of similar magnitude as anthropogenic Hg emissions to the atmosphere from fossil fuel combustion, which accounts for about half of the total global anthropogenic Hg emissions to the atmosphere. The production of primary Hg is expected to continue to decrease as an effect of increased awareness about its environmental and health effects. Economically viable Hg-free alternatives exist for practically all current Hg applications. Presently the demand for Hg is increasingly supplied by recycled Hg or by Hg obtained as a byproduct in the production of other metals such as zinc, lead, copper, gold etc. when extracted from sulphide ores, where Hg often is a trace element because of its affinity to sulphur.

Recovering Hg in the acidic flue gases from ore roasting requires a separate removal stage in addition to the one for removing other impurities, but such installations have been made in some countries thanks to environmental legislation. Further processing of the sludge generated in order to obtain metallic Hg is driven solely by market conditions. Such production of byproduct Hg from Finnish zinc production accounted in 1999 and 2000 for 8.5% and 16%, respectively, of European primary Hg production. Massive sulfide deposits in the Urals (former Soviet Union) and India also contain Hg that is, however, more likely released to the atmosphere rather than recovered during the smelting process.

Mercury may also be recovered at cyanide leaching of gold bearing ores, which is the only source of primary Hg produced in the USA since
1991 and also results in about 100 t Hg annually produced in Peru.\textsuperscript{70,116,120} In Chile, about 6 t Hg are annually reported as a byproduct from copper production,\textsuperscript{126} while Chile exported 75 t Hg to the USA in 2002.\textsuperscript{120} Australia reports no Hg production but exported 107 t Hg to the USA in 2002.\textsuperscript{120} Several countries are believed to not have reported production of Hg from copper electro refining processes.\textsuperscript{126} Further, the Peruvian Hg production from gold cyanide leaching is not reported but traded locally.\textsuperscript{71} In 2000, this was disclosed when several hundred persons claimed damages after being exposed to Hg spilled from a truck, transporting Hg from one of the mines of the company Minera Yanacocha to Lima.\textsuperscript{88} After this, the Peruvian subsidiaries of two North America based companies, Newmont Mining and Barrick Gold Corporation, disseminated information on Hg content in ore and Hg production.\textsuperscript{70,116}

Probably, environmental considerations will result in increased quantities of Hg recovered as a byproduct when processing ores destined for acquisition of other metals.\textsuperscript{95} The fate of this Hg must be addressed because of the shrinking market. It is also worth considering that the current Hg stock in the chlor-alkali plants in the EU alone corresponds to more than 50 years of production at the Spanish Hg mines at Almadén, given the production level of 236 t in 2000.\textsuperscript{44}

B. Industrial Consumption in Studied Countries

The global consumption as well as production of Hg peaked in the middle of the 20th century, although the peak in some former Spanish colonies and North America occurred earlier (Figure 2). Per capita consumption in most European countries and Japan peaked in the 1960’s and early 1970’s, but at widely different levels (Figure 2, Table 1). In Sweden, Germany,
### TABLE 1. Mercury (Hg) Consumption and Consumption Pattern in Japan, Selected European Countries, the USA, and Estimates for the Rest of the World at the Peak of Global Hg Consumption

<table>
<thead>
<tr>
<th>Year</th>
<th>Consumption (g person$^{-1}$ y$^{-1}$)</th>
<th>Chlor-alkali</th>
<th>Catalysts</th>
<th>Fungicides pesticides</th>
<th>Paper industry</th>
<th>Pharmaceutical</th>
<th>Dental</th>
<th>Laboratory</th>
<th>Electro-techn.</th>
<th>Batteries</th>
<th>Control instrum.</th>
<th>Other</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957–1960</td>
<td>10.6</td>
<td>1064</td>
<td>29.2</td>
<td>25.1</td>
<td>14.0</td>
<td>c</td>
<td>c</td>
<td>d</td>
<td>21.1</td>
<td>5.8</td>
<td>d</td>
<td>e</td>
<td>4.7</td>
</tr>
<tr>
<td>1963–1969</td>
<td>16.8</td>
<td>1666</td>
<td>34.3</td>
<td>28.1</td>
<td>11.1</td>
<td>c</td>
<td>c</td>
<td>d</td>
<td>21.0</td>
<td>3.9</td>
<td>d</td>
<td>e</td>
<td>1.7</td>
</tr>
<tr>
<td>1970</td>
<td>12.0</td>
<td>1254</td>
<td>70.7</td>
<td>0.1</td>
<td>3.0</td>
<td>c</td>
<td>c</td>
<td>d</td>
<td>19.5</td>
<td>4.5</td>
<td>d</td>
<td>e</td>
<td>2.2</td>
</tr>
<tr>
<td>1971</td>
<td>8.5</td>
<td>880</td>
<td>74.0</td>
<td>0.2</td>
<td>0.0</td>
<td>c</td>
<td>c</td>
<td>d</td>
<td>13.6</td>
<td>9.9</td>
<td>d</td>
<td>e</td>
<td>2.3</td>
</tr>
<tr>
<td>1972</td>
<td>6.5</td>
<td>600</td>
<td>60.0</td>
<td>0.0</td>
<td>0.0</td>
<td>c</td>
<td>c</td>
<td>4.9</td>
<td>/</td>
<td>4.9</td>
<td>/</td>
<td>e</td>
<td>5.1</td>
</tr>
<tr>
<td>1970</td>
<td>5.9</td>
<td>208</td>
<td>66.1</td>
<td>0.0</td>
<td>1.5</td>
<td>0.0</td>
<td>0.0</td>
<td>1.7</td>
<td>0.0</td>
<td>10.1</td>
<td>d</td>
<td>e</td>
<td>20.6</td>
</tr>
<tr>
<td>France</td>
<td>1970</td>
<td>41</td>
<td>67</td>
<td>29.9</td>
<td>0.0</td>
<td>6.0</td>
<td>0.3</td>
<td>35.2</td>
<td>0.3</td>
<td>6.0</td>
<td>0.0</td>
<td>d</td>
<td>0.0</td>
</tr>
<tr>
<td>1970</td>
<td>10.9</td>
<td>91</td>
<td>58.8</td>
<td>0.0</td>
<td>8</td>
<td>21.0</td>
<td>/</td>
<td>0.2</td>
<td>14.3</td>
<td>1.2</td>
<td>/</td>
<td>2.1</td>
<td>—</td>
</tr>
<tr>
<td>W. Germany</td>
<td>1970</td>
<td>14.9</td>
<td>902</td>
<td>24.0</td>
<td>3.0</td>
<td>4.0</td>
<td>1.0</td>
<td>13.0</td>
<td>1.0</td>
<td>3.0</td>
<td>4.0</td>
<td>26.0</td>
<td>10.0</td>
</tr>
<tr>
<td>1971</td>
<td>10.1</td>
<td>624</td>
<td>53.8</td>
<td>6.7</td>
<td>7.2</td>
<td>0.0</td>
<td>4.6</td>
<td>0.1</td>
<td>3.4</td>
<td>1.5</td>
<td>5.2</td>
<td>d</td>
<td>2.9</td>
</tr>
<tr>
<td>All W. Europe</td>
<td>1972</td>
<td>6.7</td>
<td>2243</td>
<td>52.3</td>
<td>3.1</td>
<td>12.3</td>
<td>/</td>
<td>0.1</td>
<td>4.6</td>
<td>/</td>
<td>7.7</td>
<td>16.9</td>
<td>3.1</td>
</tr>
<tr>
<td>USA</td>
<td>1972</td>
<td>8.7</td>
<td>1826</td>
<td>22.6</td>
<td>22.6</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>3.8</td>
<td>/</td>
<td>20.8</td>
<td>24.5</td>
<td>3.8</td>
</tr>
<tr>
<td>Others$^b$</td>
<td>1972</td>
<td>1.2</td>
<td>3693</td>
<td>51.4</td>
<td>/</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>/</td>
<td>35.5</td>
<td>/</td>
<td>4.1</td>
</tr>
<tr>
<td>Total World</td>
<td>1972</td>
<td>2.2</td>
<td>8454</td>
<td>46.1</td>
<td>/</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>/</td>
<td>35.5</td>
<td>/</td>
<td>4.1</td>
</tr>
</tbody>
</table>

$^a$Consumption by industry including Hg in products for export, Hg in imported consumer products is excluded.


$^c$Paint and pharmaceuticals included in “Fungicides, pesticides.”

$^d$“Laboratory” includes inorganic chemicals used in dentistry, batteries etc.

$^e$Control instruments included in “Electrotechnical.”

$^f$Not indicated.

$^g$Fungicides and pesticides included in “Paper industry.” Use in paper industry prohibited from 1969.

$^h$Data not available, marginal quantities of Hg used.

$^i$No registered production of laboratory chemicals.

$^j$HgCl$_2$ added to manganese dry cells; Hg oxide cells were not produced in Sweden.26

$^k$World excluding Japan, W. Europe, USA.

$^l$Catalysts included in “Electrotechnical.”

$^m$“Fungicides, pesticides, paper industry, pharmaceutical, dental included in “Batteries.”
the UK, the USA, and Japan, Hg consumption peaked at more than 10 g per person and year. This illustrates the presence of industries consuming large quantities of Hg, such as chlor-alkali plants with Hg cells as the basis for chemical and paper industries. In the USA, the main peak occurred a century earlier due to Hg used in amalgamation, while the industrial peak was somewhat lower than in e.g. Sweden and Japan, a result of mainly employing an asbestos diaphragm technique instead of Hg cells in the chlor-alkali plants.56 Other industrialized countries such as the Netherlands and Denmark have, generally, consumed less than 5 g Hg per person and year (Table 1), indicative of food and other industries consuming minimal quantities of Hg. For comparison, the mean consumption in less industrialized countries was about 1 g Hg per person and year in the early 1970’s, before the gold mining boom using Hg was revived (Table 1).

C. Consumption Patterns

1. AMALGAMATION

The pattern of Hg use varies widely both over time and among regions. Before the end of the 16th century, limited amounts of metallic Hg were used in alchemy and in applying gold amalgam to surfaces to be gold-plated (gilding), where after Hg was evaporated by heating.20 Silver amalgam was later used in the same way to make mirrors from glass sheets.107 The “discovery” of the new world lead to a drastically increased production of metallic Hg (Figure 1), which was mainly used for extraction of silver in Latin America and later on gold in North America (Figure 3) with the amalgamation method. This was the dominating use of Hg for more than three centuries. The production

![FIGURE 3. Consumption pattern of primary plus recycled Hg in the USA since 1851. Recycled Hg constituted 0–30% of consumed Hg before 1993, but nearly all during the end of the 1990’s. Five-year averages based on annual values obtained mainly from.120](image)
of silver in South America increased significantly after 1555, when the Hg amalgamation process was introduced.\textsuperscript{44} This drastically reduced the use of firewood, which had become scarce around the mines, and made silver extraction profitable also in the abundant silver ores with a metal content lower than the ores worked in Europe. Interestingly, mainly smelting techniques were employed for silver mining in Sweden and the rest of Europe (Figure 4), while amalgamation with mainly European Hg was performed in the Americas. With the shipment of Hg from Almadén in Spain and also from Idrija in Slovenia for use in silver mining in central and south America, about 130 000 t of Hg were sent overseas until the end of the 19th century. In addition, more than 50 000 t of Hg was produced in the Huancavelica mines in Peru. Camargo\textsuperscript{13} estimated the amount of Hg originating from Spain and Peru and consumed by Spanish-American silver miners between 1570 and 1820 to be 114 215 t Hg, which is in agreement with our earlier estimates\textsuperscript{44} and 7\% less than the estimate by Nriagu.\textsuperscript{76,77} Also after independence, silver was mainly produced with the amalgamation method in Spanish America for the rest of the 19th century. Related Hg consumption was not registered, but Nriagu\textsuperscript{77} estimated it to be 70 000 t Hg based on registered silver production of which 70\% was assumed to be extracted with Hg.

The fate of this Hg is at debate. Nriagu\textsuperscript{76,77} stated that this Hg contributes to the present day to increased Hg levels in the environment, due to continuous reemission of Hg from land and water, as suggested also by global modeling.\textsuperscript{41,50} Camargo,\textsuperscript{13} in contrast, states that Hg emitted at historic silver
and gold mining has been sequestered in deep sea sediment and is not biologically accessible any longer. Mercury used for silver and gold mining in the Americas is about half of all primary Hg historically mined. The more than a century-long time period, which has passed since historic amalgamation peaked, is a short period in geological perspectives. The fate of soil Hg bound to soil organic matter, metal oxy-hydroxides, and other soil compounds binding Hg deposited on land, is poorly known, but the influence of historic emissions is likely to last for centuries. In the temperate, boreal forest zone, Hg deposited binds initially mainly to organic matter and is mainly released when the organic matter is mobilized or mineralized. The half life for soil organic matter of the organic horizon of boreal forests is typically several decades or centuries, depending among other on climatic conditions. Further, the turnover time of organic matter varies by orders of magnitude between different fractions and thus depends on composition and heterogeneity. This is expected to result in a long and variable time-lag on the order of centuries between changes in anthropogenic Hg emissions and corresponding responses in Hg concentrations of fish and wildlife.

Although gold deposits were discovered in North America already in 1799 in North Carolina, it was the discovery of gold in California in 1847 that initiated the gold rushes in North America, culminating half a century later in Klondike in western Canada and in Alaska, which during its peak consumed about half of the global Hg production at that time. The resulting dispersal of Hg to the environment is still evident, manifested by elevated Hg contents in soils, sediments, and fish downstream historic gold mining sites, leading to restrictions on fish consumption. Most of the 63 300 t of Hg mined in the USA and Canada between 1850 and 1900 was used for gold mining in North America and Australia (Table 1, Figure 3). Cyanide leaching was introduced around 1880 and became widely used a few years after the turn of the century, but a significant use of Hg in gold mining continued for another decade (Figure 3), which is also evident from lake sediment profiles.

An increased gold price during the 1980’s boosted a new gold mining boom using Hg for amalgamation. This time the boom took place in Latin America, Central Africa, and South East Asia. An estimated 2 000 t of Hg have been dispersed in the Amazon alone during this latest gold rush, which still continues although at reduced scale in the Brazilian Amazon, due to exhausted placer deposits. As a consequence, many Brazilian gold miners are nowadays working gold deposits with the amalgamation technique in neighboring countries as we observed during numerous journeys in the region between 1982 and 2001. Large but not quantified amounts of Hg have also been used for gold extraction in China, Mongolia, and Russia (mainly Siberia) using Hg from local mines. Amalgamation is officially banned in China since 1985 and in Russia since 1990. In spite of the bans, Hg consumption
for gold amalgamation in China was estimated to 80 t in 1995, of which up to 75% may have been recycled. Sukhenko and Vasiliev report 30 t of annual Hg emissions from amalgamation in Siberia in the beginning of the 1990’s. Consumption and emissions of Hg in southeast Asia during the last goldrush is poorly quantified. According to Appleton et al., an estimated 140 t of Hg was released into the Agusan River catchment in the Philippines during the period 1986–1988 when gold mining peaked there, while there are no figures for the years before and after this period or for other parts of the Philippines or neighboring countries, where the amalgamation technique is known to be used. Ongoing efforts within the United Nations Environment Programme, the United Nations Industrial Development Organisation, and the World Bank is expected to contribute with updated quantification of the present Hg use for gold extraction globally.

Mercury used for goldmining in Africa was addressed when Communities and Small-Scale Mining (CASM) held their third annual general meeting and learning event in Ghana, 2003. The participants expressed preoccupation about the large quantities of Hg emitted by small-scale gold miners with associated damages to both human and environmental health. Annually, an estimated 500–700 t of Hg is emitted by small-scale miners, of which at least 10% is emitted in Africa, a region poorly recognized regarding Hg usage in small-scale mining (Table 2). Globally, 10–15 millions of small-scale gold miners are active, most of them using Hg. Retorts have at some places been introduced to reduce Hg emissions and thereby the health hazards for the miners, but results show that the use of retorts has not reduced the emissions of Hg to an acceptable level at the mining sites. There are an increasing number of alternative, Hg free methods on the market, being viable alternatives to continued use of Hg. However, these efforts are counteracted by the agreement between the European chloral-alkali industry and MAYASA (the company owning Hg mines in Almadén, Spain) to transfer excess Hg to Spain for reselling on the world market. MAYASA is buying this Hg for 1.2–2 US$ kg$^{-1}$, which is about 30%–40% of the world market price (4.1–4.9 US$ kg$^{-1}$ between 1996 and 2000; Figures 5 and 6) and significantly below their costs for producing virgin Hg (2.65–2.80 US$ kg$^{-1}$).

It should be noted that tailings from the amalgamation technique in some cases are submitted to cyanide leaching to recover remaining gold, thereby aggravating the environmental emissions of Hg. Muezzinoglu and Hinton et al. have recently published reviews on environmental effects of different methods used in gold mining and alternative techniques under development and implementation, so these aspects will not be treated here. Also, remediation techniques for Hg contaminated sites and Hg abatement technologies have been reviewed in Ebinghaus et al. and are therefore not repeated here.
TABLE 2. Countries with Small-Scale Gold Mines and Estimated\(^a\) Quantities of Hg Emitted from Them in 2000

<table>
<thead>
<tr>
<th>Region and country</th>
<th>Hg (t)</th>
<th>Region and country</th>
<th>Hg (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td></td>
<td>Americas</td>
<td></td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>—(^b)</td>
<td>Bolivia</td>
<td>10</td>
</tr>
<tr>
<td>Central African Republ.</td>
<td>?</td>
<td>Brazil</td>
<td>15–20</td>
</tr>
<tr>
<td>Two Congos</td>
<td>&gt;0</td>
<td>Canada and USA</td>
<td>&gt;0</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>?</td>
<td>Chile</td>
<td>1</td>
</tr>
<tr>
<td>Gambia</td>
<td>—(^b)</td>
<td>Colombia</td>
<td>30–40</td>
</tr>
<tr>
<td>Ghana</td>
<td>4–6</td>
<td>Canada and USA</td>
<td>&gt;0</td>
</tr>
<tr>
<td>Guinee Conakry</td>
<td>—(^b)</td>
<td>Ecuador</td>
<td>2</td>
</tr>
<tr>
<td>Madagascar</td>
<td>—(^b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mali</td>
<td>5</td>
<td>French Guyana</td>
<td>3</td>
</tr>
<tr>
<td>Malawi</td>
<td>&gt;0</td>
<td>Guyana</td>
<td>5</td>
</tr>
<tr>
<td>Mozambique</td>
<td>3–5</td>
<td>Peru</td>
<td>20–35</td>
</tr>
<tr>
<td>Senegal</td>
<td>—(^b,c)</td>
<td>Suriname</td>
<td>8</td>
</tr>
<tr>
<td>South African Republ.</td>
<td>0.5</td>
<td>USA</td>
<td>&gt;0</td>
</tr>
<tr>
<td>Sudan</td>
<td>3–5</td>
<td>Venezuela</td>
<td>10–15</td>
</tr>
<tr>
<td>Tanzania</td>
<td>10–15</td>
<td>Central America</td>
<td>2–5</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>10–20</td>
<td>Sum</td>
<td>&gt;106–144</td>
</tr>
<tr>
<td>Sum</td>
<td>&gt;36–57</td>
<td>World total</td>
<td>&gt;487–696</td>
</tr>
</tbody>
</table>

\(^a\)Estimates from different persons participating in the CASM meeting in Ghana, September 2003. Small-scale gold mining was not known to be significant in countries not mentioned.

\(^b\)Mercury not used by tradition and conservatism.

\(^c\)Law banning the use of Hg for gold mining.

\(^d\)Figure for 1997.34

2. PIGMENT AND ORGANIC FUNGICIDE PRODUCTION

Cinnabar (HgS) has been used in its natural state as a pigment and also as a drug and preservative for several thousand years.\(^{57}\) The use of the bright red/orange pigment ranged from temples and the emperor’s palaces to seals stamped on paper money already more than 1000 years ago in China. Quantities of cinnabar mined for these purposes in China are not recorded. In Idrija, the pigment production corresponded to 7 628 t of metallic Hg during a 500-year period.\(^ {15}\) Most of this production was vermilion (cinnabar produced from elemental Hg). This was important also in the US, where 195 t Hg were sent to New York in 1882 for production of vermilion, nearly as much as used in gold and silver mining (205 t) in the USA during the same year.\(^ {120}\) Another indication of the importance of vermilion at that time is that similar amounts of Hg (239 t in 1882) were exported from USA to China.
FIGURE 5. Prices of Hg in Europe and in the Americas over five centuries. Initial intercontinental differences reflect the high costs for transportation. Pre-1800 prices show the low and stable monopoly price controlled by the Spanish state for more than two centuries. European prices for Almadén until 1640 and London 1850–1893, 1957–2000; American prices for Mexico City until 1849, San Francisco 1850–1905, New York 1906–2000. Compiled from 5,36,92,97,117,120

FIGURE 6. Levels and fluctuations of Hg production, consumption, and price in the USA, the largest consumer nation. The USA was also the largest producer nation in the 1850’s until the 1880’s, after which several Hg mineral resources became depleted. Ten major price peaks were discernible and described in the text. The price plunged after 1965, while consumption continued at a high level until 1990. Compiled from 117,120 See methods section for further details.
The American vermilion industry continued to be a large consumer of Hg for the rest of the 19th century (Figure 3), but was later reduced and in the 1940’s entirely replaced by less expensive compounds such as antimony sulphuret, red lead, and hematite. Organic Hg compounds are efficient biocides, which were added as an antifouling agent to paints, as a slimicide to paper pulp and as a fungicide to protect seeds and plants from fungal diseases. In Sweden, these applications started in the 1940’s and the production grew rapidly, so that half of the 140 t Hg annually imported in the end of the 1950's were used to produce biocides, mainly for the pulp and paper industry (42% of the annual Hg imports), while antifouling paint used 2% of imported Hg, and agricultural chemicals used 6% (Figure 4, specification not shown). Two thirds of the agricultural chemicals produced in Sweden were exported, among others to Denmark, which contributed to the low industrial Hg consumption in Denmark (Table 1). This minor use of Hg in agriculture caught the public attention by killing birds and terrestrial animals as already described. As a result, Hg was excluded from all slimicides from the end of 1967, from all antifouling paints for boats sold after 1973, and from all fungicides used in agriculture after 1988, when the National Chemicals Inspectorate did not prolong the registration of a Hg-containing fungicide, occasionally used as an exception from the ban of Hg fungicides from the 1970’s.

The trend was similar but with a smaller amplitude in the USA, where 17% of totally 1830 t Hg consumed per year was used for organic Hg compounds in the end of the 1950’s, divided between slimicides using 3%, antifouling paint using 4%, and agricultural chemicals, including insecticides, using 11% (Figure 3; specification not shown). The figures reflect the smaller relative importance of forestry and larger relative importance of agriculture in the economy of the USA. While the use of Hg-free slimicides and agricultural biocides was introduced at about the same time in the USA as in Sweden, the production of antifouling paint in the USA shows a diverging development by more than tripling until the 1980’s, after which also this use of Hg decreased. In 1993, EPA canceled registrations of the last two Hg-containing fungicides at manufacturer’s request.

3. CHLOR-ALKALI INDUSTRY

Global Hg production increased markedly in the 20th century, due to industrial use other than for gold and silver mining (Figures 1, 3, 4). One of the main consumers was and still is the chlor-alkali industry, where Hg cells are used for production of chlorine, hydrogen, and sodium (in a few plants potassium) hydroxides by electrolysis of a brine solution. In 1996, approximately 1 344 t Hg, 40% of all Hg produced, was consumed by the world’s chlor-alkali industry and has recently decreased to an estimated 30% or lower, since West European and North American chlor-alkali industry
reported 173 t consumed in 2000, corresponding to 9.4% of Hg produced. Quantities of Hg consumed by chlor-alkali industries in other parts of the world remain to be reported. While 53% of the chlorine and alkali production in Europe is still done with Hg cells, the corresponding figure for the USA is about 10%, while Japan has produced all chlorine and alkali with Hg-free technologies for more than 15 years already. Measured direct emissions to air and water from chlor-alkali plants have decreased substantially during the past years, especially in western Europe and North America, but are still amounting to about 10 tons a year in western Europe. In addition, large amounts of Hg-containing sludge are produced, which may explain much of the Hg consumption of 135 t per year by West European chlor-alkali plants. Only about 10% of the reported Hg consumption was accounted for as emitted or entering the products. Mercury in the sludge was reported as unaccounted until a few years ago, when a new routine was introduced for reporting to the national and regional authorities. Potential releases of Hg from these wastes are of concern. If wastes are deposited in landfills instead of recycling the Hg, the waste producers should reserve funds for the costs of future generations to maintain these sites.

Using Hg cells is not the economically most favorable technology for production of chlorine and sodium hydroxide any longer. The alternative membrane technology does not use or emit any Hg and in addition has lower energy consumption. It is regarded socially as well as economically feasible to convert all chlor-alkali plants in the EU to Hg-free technology already by 2007 (Dir. Jean-Marie Cadiou and Head of Unit Per Sørup, Institute for Prospective Technological Studies, at a EU Joint Research Centre presentation in Stockholm, 15 March 2001). Further, contracting parties in the Paris Commission Decision 90/3 of 14 June 1990 on Reducing Atmospheric Emissions from Existing Chlor-Alkali Plants agreed that “the objective is that they (the Hg cells) should be phased out completely by 2010.” While several companies have infrastructure with Hg cells still operable, Euro Chlor presently advocates a delay of the final phase-out date. Nevertheless, the two remaining Swedish chlor-alkali plants with Hg cells are due to conversion before 2010, and it is expected that Hg cells, the main consumer and polluter for a century, will worldwide be entirely replaced within a few decades.

4. USES IN EXPLOSIVES, ELECTRICAL AND MEASURING APPLIANCES

Hg fulminate [Hg(ONC)₂], which was discovered by Howard in 1799, became widely used in percussion and blasting caps in the 19th century, since it was the initial detonator in the caps invented by Nobel in the 1860’s. They were used for dynamite and other explosives with widespread use in mining and construction of canals, roads, and railways and in ammunition.
Just before World War I, the USA consumed 250–300 tons, more than one third of actual Hg consumption in the USA, in their production of fulminate (Figure 3). Since dry fulminate is extremely sensitive to thrusts, it had to be produced at the assembly sites of percussion and blasting caps. Sweden imported most caps assembled, but produced the fulminate needed for additional caps at a couple of factories for explosives, which are estimated to have consumed 0.7 tons Hg per year around 1940 corresponding to about 2% of imported Hg (Figure 4). This has not been accounted for in earlier inventories on Hg use in Sweden, and although it makes up a minor quantity in Sweden, warrants an assessment of the quantities of Hg consumed for fulminate production in Germany and UK, where the production of percussion and blasting caps for both national demand and a substantial export was large at the time. After World War II, fulminate was replaced by lead azide and nitrogen tetrasulphide. In Sweden, fulminate production was terminated in 1959.

Before the ban in 1992, Sweden imported clinical thermometers containing large quantities of Hg, while smaller quantities of Hg were used in domestic production of other thermometers, measuring instruments and rectifiers (Figure 4). In Sweden, Hg use for measuring instruments and electrical products was large between World Wars I and II, while corresponding use in the USA dominated for a longer period and still is large as a result of aversion of several producers to replace Hg-containing thermometers, thermostats for housing, and switches in cars with Hg free ones (Figures 3 and 4). However, this use is on change also in the USA, where several states have recently introduced bans on the manufacture, sale and distribution of Hg fever thermometers and Hg-added novelty items. Comparatively small amounts of Hg are still used for fluorescent tubes in both Sweden and the USA, although the emissions to the environment from used tubes are significant if they are not recycled without breakage of the tubes.

The consumption of Hg for production of Hg-oxide batteries and of alkaline batteries, to which HgCl₂ was added to improve performance and shelf life, increased drastically in the 1980’s in the US, Japan, and some West European countries (Table 1, Figures 3 and 4). In Japan, 65% of the Hg consumed in 1990 was used for battery production. In contrast, Sweden had no domestic production of Hg-oxide batteries, and only limited amounts of Hg were consumed for production of manganese dioxide batteries, while considerable quantities of batteries containing Hg were imported. In order to reduce Hg emissions from waste incineration and diffuse emissions, the authorities in most industrialised countries enforced legislation in the 1990’s, banning both production and import of Hg-containing batteries with a few exceptions, such as certain batteries for hearing aids and button-cells containing less than two percent Hg by weight, which are permitted in the EU until 2004.
5. MEDICAL AND DENTAL USES

The dominating medical use of Hg, (in metallic form and as calomel, Hg₂Cl₂), in Sweden in the second half of the 19th century (Figure 4) indicates that some persons were highly exposed to Hg, mainly for treatment of syphilis, and 0.3–1% of the population of 3.5–5 millions were treated for venereal diseases (10 000–50 000 persons). However, the per capita consumption of Hg was low in Sweden during this period, contrary to the USA (Figure 2), where most Hg was used in gold mining (Figure 3), causing direct human exposure when Hg is emitted as vapor during the burning process. The total number of persons engaged in gold mining in the USA is not known, but in 1899 between 50 000 and 100 000 gold miners rushed to Yukon Valley in Alaska and western Canada.

Sublimate (HgCl₂) is in certain countries still used as an antiseptic for wounds. It was used in large quantities during the World Wars, triggered by the largely increased use of Hg in explosives, as indicated by the peaks in Figure 1. Sublimate was also used for preserving wood. Nowadays, the use of Hg in medicine, pharmaceutical products, and gold mining has been prohibited or restricted in industrialized countries, but is still a topic of large concern for the population in many other countries, and needs to be acted upon in order to reduce human exposure. For example, Thimerosal (ethylmercury thiosalicylate) used for preserving vaccines in many countries should be refrained from administering to children, being most vulnerable to Hg. The use of Hg-containing skin lightening soaps, creams, and powder for adults and babies should be ended immediately. This legal production in the EU for export to Africa and India continued for several years after that the domestic sale had been banned, indicating an example of double standards in the EU.

Mercury has been extensively used in dentistry during the last century, after that the modern amalgam was introduced in the USA in the 19th century. In Sweden, the use of amalgam increased dramatically after decisions in 1938 of free dental care for children and in the 1950’s for pregnant women. Presently, dental amalgam accounts for 10% of Hg used in the USA and one third of Hg used in Sweden (Figures 3 and 4). Multinational political actions, similar to those against the use of Hg in batteries, have not been directed towards the use of amalgam for dental fillings, despite economically viable alternatives and large and well-documented emissions to both air and water. Mercury emissions to the air from cremation are estimated to 0.28 t yr⁻¹ in Sweden, or 0.03 g per capita per year from a population of 8.5 million with 40–100 t of Hg in dental fillings and a cremation rate around 65%. Mercury losses to waters from amalgam fillings via human feces amount to about one third of that to the air, while losses to waters from dental practices are not quantified in Sweden but could be larger and are of concern for sewage treatment plants. In Denmark with 5.4 million
inhabitants, Hg losses to water from dental practices were estimated to be between 83 and 120 kg per year in 1992/93. An estimated 20% of Hg consumed as dental amalgam is lost within a 10-year period. This indicates that of 108 t of Hg consumed for dental applications in Sweden during the 1970’s (Figure 4), about 20 t could have polluted the environment until the end of the 1980’s. Dental use of Hg has been significant also in Japan and most European countries (Table 1). Part of the demand in the EU has been supplied by Swedish companies, exporting dental amalgam when the demand in Sweden decreased during the latest decade. Dental amalgam is classified as a medical product according to EU legislation and consequently exempted from the Swedish export ban of Hg, compounds, mixtures, and products containing Hg. Swedish efforts to reduce the use of dental amalgam beyond voluntary agreements by legislation have been hindered by economic interests profiting on the continued use of amalgam. Considering that some persons evidently suffer from dental amalgam and that researchers have been able to show effects of inorganic Hg at lower concentrations than before, it seems appropriate that the amalgam producers set aside funds for treatment and convalescence of patients affected by amalgam, instead of leaving this costs to the public (tax general payers).

D. EVALUATION OF UNCERTAINTIES INVOLVED IN FIGURES USED

In general, contemporary records on produced or consumed quantities are the most reliable figures possible to obtain, although attention needs to be paid to the various units used and to any changes in reporting practices. The figures on Hg produced in Spain and Slovenia from 1500 to present and in Spanish America until 1820 are expected to correspond to actually produced quantities, because these were carefully recorded due to the value of Hg and its importance in the Colonial and European economies. Production of Hg at North American mines has been equally well registered since Hg mining did not start until just before 1850. Mercury production in Algeria and Italy has a shorter and well documented output. Production figures from the other two main producer regions, China and the countries of former Soviet Union, are missing for long periods and are based on exported quantities or estimated production for other periods, which may be misleading. However, figures reported from the countries of the former Soviet Union for the most recent decade are based on produced quantities.

The consumption records presented are, in general, less certain than the production records due to a large number of consumers ranging from industries to craftsmen and individuals. Official statistics on Hg consumption is available since the second half of the 19th century in both Sweden and the USA, although less detailed in the beginning. Reliability of the figures
improved when the consumers later on had to report quantities of Hg consumed in specific categories. Still, a certain degree of uncertainty remains due to the possibility of not reported quantities or reported quantities not corresponding to consumed quantities. However, this uncertainty is probably small, and smaller than that caused by public databases being made inaccessible to protect company proprietary data in market sectors with few (three or less) actors, such as the dental sector in Sweden and Hg byproduction in the USA. If the ongoing merging of companies results in an increasing number of areas where data are inaccessible, governmental restriction of public information on industrial activities, harmful or potentially harmful to human and environmental health, inflicts on fundamental values of democracy.

E. ECONOMICS AND POLITICAL INFLUENCE ON PRICES

The performance of the global Hg market for the last five centuries has been diverging from the market of most other commodities. For nearly three centuries, 1560–1830, a global monopoly situation and a constant lack of Hg prevailed, but despite this the selling price was kept constant at a level to barely match production costs, since Spain controlled the Hg price from 1572 in western Europe and the Americas in power of its dominating position as the largest producer and a monopoly on Hg trade with the Spanish Americas. Initially, prices escalated from 1559, but the market became saturated after a few years and competition with the Hg mine in Peru caused receding prices. The price was in 1572 fixed at current market price, but was later on lowered to correspond to estimated production and transport costs, but without covering administrative costs or generating any profit. In this way, the Spanish crown wanted to stimulate the production of silver. The transport costs were high in the 16th century, indicated by large difference in Hg price between Almadén and New Mexico (Figure 5). After 1590, prices decreased gradually (except for 1607–1608) until the Spanish monopoly ceased in the beginning of the 19th century. Then the Hg price initially rose sharply, but declined again rapidly around 1850, when Hg mining finds were discovered in North America (Figure 5). Later on it oscillated according to availability and demand with an overall increasing trend in the 20th century until the mid-1960’s, and for more than a century, consumption was more important than production in governing the price. For example, when amalgamation was replaced by more efficient cyanide leaching in the end of the 19th and the beginning of the 20th centuries, the Hg price dropped (Figure 5) and USGS stated in 1884: “The quicksilver industry is in a depressed condition. The production has fallen off largely, but this has not had the effect of stimulating prices...”. Efforts were made to find new applications for Hg other than amalgamation or production of vermilion. Innovations technically successful were the use of Hg as an electrode in electrolysis, use in other electrical appliances, in dentistry, instrumentation, and as ballast at navigation and the development of inorganic and organic Hg compounds, which were used in
industrial processes as catalysts, in explosives, in health care (disinfectants, skin bleaching), in paint to ships for antifouling, and in other paint, agriculture, and industry as fungicides (including slimicides at paper production). Other inventions were less successful, such as replacing water by Hg in utility burners, which resulted in large emissions of the comparatively expensive Hg when the burners exploded and in a lower efficiency than for improved burners using steam.\textsuperscript{120} Wars caused elevated Hg prices (Figure 5) due to increased consumption of Hg used for pharmaceuticals and various kinds of explosives (Figure 5), thereby spurring the production to new peaks during WWII and the Vietnam War (Figure 1).

In the 1970’s, an awakened environmental concern caused a significant decrease in global demand of Hg, and the price plunged drastically (Figures 2 and 5). Consumption of Hg was less reduced in the USA than in Sweden (Figures 2 and 6). In the end of the 1980’s, western Europe, the US, and Canada restricted the use of Hg further by reducing the permitted Hg content in batteries (dry and button cells), which was later on followed by Japan and other countries (Figures 3 and 4). European and Japanese car manufacturers replaced Hg switches with Hg free ones, and Japan phased out all the Hg cells while chlor-alkali plants in other industrialized countries reduced their emissions.\textsuperscript{56,111} The dominating Hg producer, the Spanish state company MAYASA, running the mines at Almadén, responded by forcing up the Hg prices in 1987–88 by retaining Hg produced in stock.\textsuperscript{16,120} However, these efforts were punctured by uncontrollable sales of stocks from the former USSR countries after a drastic reduction of the military arsenal.\textsuperscript{16,120} When this Hg and new Hg from mines in the former USSR countries entered the global Hg market, the price plunged further (Figure 5). MAYASA had to close down in 1990 after several years of losses.\textsuperscript{55,120} Other mines in Italy, USA and later on in Slovenia closed, too, but as in the 1880’s, the low production could not stimulate the prices, which remained low and have been just above 4 US$ kg\textsuperscript{−1} Hg during the last years of the 20th century.

Another anomaly of the Hg market was demonstrated in 1993, when MAYASA, assisted by public subsidies, reopened the mines in Almadén, Spain, in spite of a continued low Hg price and a declining demand of Hg.\textsuperscript{43} The following years, MAYASA got additional subsidies from EU.\textsuperscript{24} The other major Hg mines in operation at the end of the 20th century in Algeria, China, and Kyrgyzstan are also state owned and for political reasons inclined to producing Hg even at economic losses.\textsuperscript{120} One negative consequence of this is that virgin Hg may be used instead of recovering Hg from waste generated by e.g. Hg cells in chlor-alkali plants, unless environmental legislation enforces recycling.

The index-corrected world market or global Hg price varied widely. Globally, four periods can be discerned: (i) the colonial period when most Hg was produced in Europe or under European control in Spanish America for
use, mainly, in silver mining; (ii) the gold rush period when both production and consumption were dominated by the USA and additional gold mining in Canada, Australia and Africa; (iii) the industrial period including the two world wars, and (iv) the recent decades of environmental awareness in the industrialized countries.

Comparisons show that global Hg price and production was controlled accordingly by different forces: During the first period, both price and production were controlled by central, political authorities except for the last three decades, during the second and third periods by the rules of capitalism and war, and during the fourth period by the public opinion. This is reflected in the relationship between price and production. During the colonial period, the Hg price was constant for decades or even a century and a half despite changes in production. The collapse of the Spanish empire ended the epoch of fixed Hg price and resulted in a rapidly increasing price, driven by continued silver mining and gradually accelerated by the demand from gold miners in North America, raising the price to the highest for two centuries and a half. During 1850–1970, after the discovery of mineable Hg in the USA, the Hg price showed no clear, long-term trend until 1970, but fluctuated widely with an amplitude of about five-fold. At the same time, global production varied about ten-fold (Figure 1).

Ten peaks in price and Hg production in the USA can be discerned (Figure 6, Table 3). The first four can be linked to gold rushes, one of them possibly also to the civil war. Three peaks in price can be linked to the world wars and the inter-war recession, bringing about a price peak just before the depression in the 1930's, and two to the post-war industrialization, strengthened by the Korea and Vietnam wars (Figure 6). Finally, there is a smaller but distinct peak in the beginning of the 1980's. Linked to each price peak, also production showed a peak. During both world wars, prices increased dramatically and simultaneously with production, demonstrating a rapid response to a sudden change in economy. With the other peaks, however, production increased quite clearly after an increase in price, suggesting that production was controlled by demand, with a time lag of generally two–five years (Figure 6). After 1970, patterns changed dramatically following a collapse of the Hg price to the lowest level during history. At the same time, production in the USA collapsed, but recovered soon and reached another peak in the end of the 1970's and beginning of the 1980's, thereby preceding the corresponding price peak in 1981. This inverse production-price reaction appears to be related to a continued large demand for Hg also after 1970 and the discovery of new Hg deposits.

The Hg market in the USA, the largest national market, shows a close relationship between consumption and price for almost a century until after World War II (Figure 6). An expected consumption-driven price-increase is most evident in the 1920's, the post-war period until the mid 1950's,
and in the beginning of the 1960’s. Other forces than market forces appear to have driven up the price in the beginning of the 1870’s, possibly the German-French war, and during both world wars. The drastic price decrease in the 1970’s shows that the price reacted immediately and entirely in accordance with the increasing knowledge acquired about health and environmental effects of Hg, while the consumption reacted more sluggishly and thereby recalled a higher price within a few years in the beginning of the 1980’s before also the consumption plunged (Figure 6). This large decrease in consumption forced the Hg price down to the lowest level ever. Ever since Hg started to be mined in the USA, production was in the 19th century larger than domestic consumption, some periods twice as large. However, in the second half of the 20th century, domestic production was far from meeting domestic consumption (Figure 6) and an increasing quantity had to be supplied from European mines. This did not cause any markedly different

### TABLE 3. Correlation of Hg Price (in San Francisco Until 1905, Thereafter in New York, Index-Corrected) to Hg Consumption and Production in the USA and to World Production for Three Different Periods: 1855–1944, When the USA Was a Net Exporter of Hg, 1945–1965, When the USA was a Net Importer, and 1966–2000, After an Apparent Change of Market Rules in 1965. Pearson Correlation Coefficients Based on Annual Values, Bold Numbers are Significant at the 5% Level

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>USA consumption current year</td>
<td>0.30</td>
<td>0.51</td>
<td>0.74</td>
</tr>
<tr>
<td>USA consumption preceding year</td>
<td>0.17</td>
<td>0.61</td>
<td>0.73</td>
</tr>
<tr>
<td>USA consumption succeeding year</td>
<td>0.38</td>
<td>0.27</td>
<td>0.71</td>
</tr>
<tr>
<td>USA, change in consumption current year vs. preceding year</td>
<td>0.15</td>
<td>−0.09</td>
<td>0.06</td>
</tr>
<tr>
<td>USA production current year</td>
<td>0.05</td>
<td>0.13</td>
<td>0.56</td>
</tr>
<tr>
<td>USA production preceding year</td>
<td>−0.09</td>
<td>−0.18</td>
<td>0.53</td>
</tr>
<tr>
<td>USA production succeeding year</td>
<td>0.22</td>
<td>0.42</td>
<td>0.54</td>
</tr>
<tr>
<td>USA, change in production current year vs. preceding year</td>
<td>0.30</td>
<td>0.56</td>
<td>0.07</td>
</tr>
<tr>
<td>USA production current year/USA consumption current year</td>
<td>−0.12</td>
<td>−0.12</td>
<td>0.26</td>
</tr>
<tr>
<td>USA production current year/USA consumption preceding year</td>
<td>−0.04</td>
<td>−0.12</td>
<td>0.29</td>
</tr>
<tr>
<td>USA production current year/USA consumption succeeding year</td>
<td>−0.14</td>
<td>−0.04</td>
<td>0.17</td>
</tr>
<tr>
<td>World production current year</td>
<td>0.38</td>
<td>0.58</td>
<td>0.81</td>
</tr>
<tr>
<td>World production preceding year</td>
<td>0.31</td>
<td>0.62</td>
<td>0.86</td>
</tr>
<tr>
<td>World production succeeding year</td>
<td>0.36</td>
<td>0.46</td>
<td>0.75</td>
</tr>
<tr>
<td>World, change in production current year vs. preceding year</td>
<td>0.13</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td>World production current year/USA consumption current year</td>
<td>−0.02</td>
<td>−0.05</td>
<td>0.33</td>
</tr>
<tr>
<td>World production current year/USA consumption preceding year</td>
<td>0.07</td>
<td>−0.04</td>
<td>0.45</td>
</tr>
<tr>
<td>World production current year/USA consumption succeeding year</td>
<td>−0.08</td>
<td>0.19</td>
<td>0.34</td>
</tr>
</tbody>
</table>
correlation between consumption and the rising price trend until 1965 (Table 3). A marked trend shift took place when the Hg price peaked in 1965 (Figure 6; Table 3). As both knowledge and awareness about health and environmental impact of Hg increased, political decisions in Japan, Sweden, and other countries contributed to reverse the price trend. Uncertainty and fear among the Hg consumers about further complications of continued Hg use may have contributed to the much faster fall in price than in actual Hg consumption (Figure 6).

Although the Hg prices in New York and London were highly correlated \((r = 0.85)\), the price in New York fell more rapidly than the price in London after 1965 (Figure 5). A possible cause is that the state owned, mainly European mines, supplying Hg sold via London, were less sensitive to market forces than the mines in the USA, which were all private companies.\(^{120}\) In addition, a continued large demand for Hg by the European chlor-alkali industry, the dominant consumer by that time, may have damped the price fall in London.

After 1965, the fall of the Hg price was significantly correlated with reduced Hg consumption in the USA \((r = 0.74)\) and also globally, if assuming that global production reflects global consumption (Table 3). This indicates a marked decrease in the demand for Hg, which should have alerted producers to reorganize their activity. This was not initiated at Almadén until 1979, when an ambitious program to develop the exploitation of Hg and to diversify the activities of the company into agriculture and public works services took off.\(^{33}\) The government paid 2/3 of the budget but had later on, as the owner, to also assume the losses, which were partly offset as a 15 times enlargement of social capital.\(^{33}\) Although improvements of infrastructure is an appropriate area for public intervention, the lack of transparency and clear borders between public benefits and the loss making Hg production, no involvement of the private sector and a lack of sound economic principles turned out to be fatal for the program, and as a results, the mining company and region is now suffering from an aggravated recession. Between 1985 and 1997, the Hg mining company received subsidies amounting to 150.8 millions US$, of which 59.7 millions US$ were used to support the mining and production of mainly Hg involving losses, thereby sapping market forces of Hg.\(^{33,65}\) Spain has received large sums from the EU structural funds since 1994 (typically 5 000 millions US$ annually), but it has not been possible to trace the partition transferred to the mining sector of MAYASA.

Between 1965 and 2000, the decreasing Hg price was strongly correlated with production of Hg and driven by the reduced consumption (Table 3). The present low Hg price may be fatal for the environment, by stimulating the use in gold mining and other dissipative uses and by reducing any economic incitements for recycling Hg after use.
IV. CONCLUSIONS AND RECOMMENDATIONS

When phasing out Hg from industrial and other uses, stockpiles of Hg need to be safely disposed with minimal emissions to the environment. Mining waste and tailings containing considerable amounts of Hg are abundant in the region of the mercuriferous belt between the western Mediterranean and central Asia, as well as in the western part of South and North America. At the Idrija Hg mine in Slovenia, an estimated 40 000 t of Hg have accumulated in waste. Large but not yet quantified amounts are present around mines extracting Hg, copper, gold and other metals in Spain, Italy, and other mining regions worldwide, being potential Hg emitters. To give an example, more than one million tons of tailings and oxidized ‘hot rocks’ (roasting plant waste) from a Hg mine in the Philippines was used in the 1960’s for the construction of a coastal jetty, which continues to increase the Hg concentration in adjacent water.

A compilation of Hg in industrial waste in Sweden suggests 280 t of Hg in 5000 t of mining waste containing more than 1% Hg, 800 t of Hg in mining waste with 0.0001–1% Hg, 8 t of Hg in steel industry waste containing about 0.0004% Hg, 8 t of Hg in waste from the paper and pulp industry containing about 0.0007% Hg, and 13 t of Hg in deposits at former chlor-alkali and paper pulp factories. The Swedish mining waste with 1% Hg or more and some mining waste with lower Hg concentration but being a risk to the environment has been decided to be safely stored in a deep bedrock repository to minimize future environmental and health risks. In the USA, sales of Hg from the National Defense Stockpile were suspended in 1994 and remain suspended pending completion of an analysis of the potential environmental impact of the sales, and continued storage in ware houses has been suggested as an option.

Another challenge for the near future is the disposal of the large stocks of Hg currently in use, notably the 12 000–15 000 t of metallic Hg used as electrodes in West European chlor-alkali plants with Hg cells. For a safe disposal, national and international authorities need to set up a framework of regulations to protect the environment and public health, while the responsibility for the development of specific technical solutions may remain with the industry and waste owners. As decided in Sweden, Hg-containing wastes will be permanently stored in a deep bedrock repository in order to minimize emissions to the environment, and an abandoned mine with suitable geological and hydrological characteristics may be used as a deposit. One possibility of disposing the large quantity of Hg in European chlor-alkali factories is to return it back to its main origin, the mines of Almadén, for appropriate treatment and final deposition. Recombining Hg with sulfur to form cinnabar (HgS) will reduce its mobility, a technique that has been practiced for more than a century when producing vermilion, and will produce a...
natural compound that can be safely stored, for example in abandoned Hg mines. The presence of carbonates in the host rocks of Almadén will minimize local environmental hazards for millennia to come as it has done for passed millennia. In this way, the flow of mined Hg would be reversed in an environmentally profitable way with the turn of the millennium, about 500 years after its entry as a significant global pollutant.

ACKNOWLEDGMENTS

The study was partly financed by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) and by Helge Ax:son Johnssons Stiftelse. The Swedish Foundation for International Cooperation in Research and Higher Education (STINT), Centre for Metal Biology, Uppsala, Environment Canada, the International Atomic Energy Agency (IAEA), the Swedish Institute (SI), and the Dept. of Research Cooperation at the Swedish International Development Agency (Sida/SAREC) are acknowledged for research and travel grants to the first author. This study is linked to efforts supported by the Swedish Environmental Protection Agency to reduce European mercury emissions. We would like to thank Ingegerd Gustafsson and Kjell-Ake Larsson for data from the archives of Dyno Nobel and NEXPLO Bofors AB, respectively, Arne Jonsson for supplying literature not available at libraries and Vesna Jereb, Jožef Stefan Institute, Slovenia, for translating Slovenian articles. We also gratefully acknowledge Prof. John Jay TePaske, Duke University, USA, and Dr. Felix Hruschka, Proyecto GAMA, Gestión Ambiental en la Minería Artesanal, Lima, Peru, for statistical data.

REFERENCES


The Rise and Fall of Mercury


67. Meili, M., Bishop, K., Bringmark, L., Johansson, K., Munthe, J., Sverdrup, H., and de Vries, W. Critical levels of atmospheric pollution: Criteria and concepts


The Rise and Fall of Mercury


