8 Prevention and control technologies and practices

8.1 Overview

600. This chapter summarizes information submitted from around the world about prevention and control technologies and practices, and their associated costs and effectiveness, that could reduce and/or eliminate releases of mercury, including the use of suitable substitutes, where applicable.

601. As noted in chapter 6, the sources of releases of mercury to the biosphere can be grouped in four major categories (including the last category, that is not clearly explained in many reviews of the subject):

- Natural sources - releases due to natural mobilisation of naturally occurring mercury from the Earth's crust, such as volcanic activity and weathering of rocks;
- Current anthropogenic (associated with human activity) releases from the mobilisation of mercury impurities in raw materials such as fossil fuels – particularly coal, and to a lesser extent gas and oil – and other extracted, treated and recycled minerals;
- Current anthropogenic releases resulting from mercury used intentionally in products and processes, due to releases during manufacturing, leaks, disposal or incineration of spent products or other releases;
- Re-mobilisation of historic anthropogenic mercury releases previously deposited in soils, sediments, water bodies, landfills and waste/tailings piles.

602. Figure 8.1 shows graphically these primary release categories, together with the main alternatives for preventing and controlling releases.

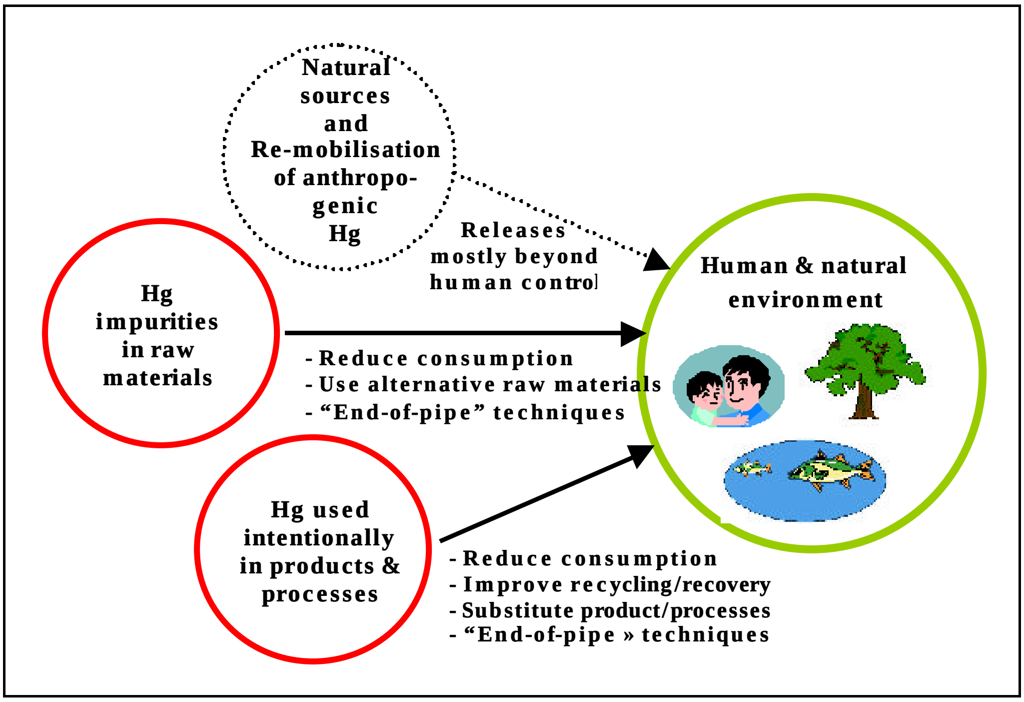

Figure 8.1 Key sources of mercury releases to the environment, and main control options.

603. Releases due to natural mobilisation of mercury and re-mobilisation of anthropogenic mercury previously deposited in soils, sediments and water bodies are not well understood and are largely beyond human control. The other two categories are current anthropogenic mercury releases. Reducing or eliminating these releases may require:

- Investments in controlling releases from and substituting the use of mercury-contaminated raw materials and feedstocks, the main source of mercury releases from unintentional uses; and
- Reducing or eliminating the use of mercury in products and processes, the main source of releases caused by the "intentional" use of mercury.

604. The specific methods for controlling mercury releases from these sources vary widely, depending upon local circumstances, but fall generally under the following four groups:

A. Reducing mercury mining and consumption of raw materials and products that generate mercury releases;
B. Substitution (or elimination) of products, processes and practices containing or using mercury with non-mercury alternatives;
C. Controlling mercury releases through end-of-pipe techniques;
D. Mercury waste management.

605. The first two of these are "preventive" measures – preventing some uses or releases of mercury from occurring at all.[17] The latter two are "control" measures, which reduce (or delay) some releases from reaching the environment. Within these very general groupings are a large number of specific techniques and strategies for reducing mercury releases and exposures. Whether or not they are applied in different countries depends upon government and local priorities, information and education about possible risks, the legal framework, enforcement, implementation costs, perceived benefits and other factors.

A. Reducing consumption of raw materials and products that generate mercury releases

606. Reducing consumption of raw materials and products that generate mercury releases is a preventive measure that is most often targeted at mercury containing products and processes, but may also result from improved efficiencies in the use of raw materials or in the use of fuels for power generation. This group of measures could potentially include the choice of an alternative raw material such as using natural gas for power generation instead of coal, or possibly by using a coal type with special constituents (such as more chlorine) because the mercury emissions from burning this type of coal might be easier to control than other coal types.

607. Another possible approach in some regions might be the use of coal with a lower trace mercury content (mercury concentrations appear to vary considerably in some regions depending on the origin of the raw materials). However, there are some limitations and potential problems with this approach. For example, in the case of the utility preference for low-sulfur crude oil, it is likely that some utilities might be willing to pay more for low-mercury coal, which effectively lowers the market value of all high-mercury coal, which in turn might lead to higher consumption of high-mercury coal in regions where utilities have less rigorous emissions controls. Moreover, data collected recently in the US indicate that coal supplies in the US do not vary significantly in mercury content.

608. Nonetheless, such preventive measures aimed at reducing mercury emissions are generally cost-effective, except in cases where an alternative raw material is significantly more expensive or where other problems limit this approach.

[17] "Pollution prevention" refers to any practice which reduces the amount of a pollutant entering the waste stream or otherwise released to the environment prior to recycling, treatment, or disposal. It can include a wide range of activities, such as toxics use reduction, material substitution, process or equipment modification, and better management practices.

B. Substitution of products and processes containing or using mercury

609. Substitution of products and processes containing or using mercury with products and processes without mercury may be one of the most powerful preventive measures for influencing the entire flow of mercury through the economy and environment. It may substantially reduce mercury in households (and reduce accidental releases, as from a broken thermometer), the environment, the waste stream, incinerator emissions and landfills. Substitutions are mostly cost-effective, especially as they are demanded by a larger and larger market. This group of measures would also include the conversion of a fossil-fueled generating plant to a non-fossil technology.

610. At the same time, it would be a mistake to assume that substitution is always a clear winner. For example, in the case of energy-efficient fluorescent lamps, as long as there are no competitive substitutes that do not contain mercury, it is generally preferable from a product-life-cycle perspective to use a mercury-containing energy-efficient lamp rather than to use a less efficient standard incandescent lamp containing no mercury, as a result of current electricity production practises.[18]

C. Controlling mercury emissions through end-of-pipe techniques

611. Controlling mercury emissions through end-of-pipe techniques, such as exhaust gas filtering, may be especially appropriate to raw materials with trace mercury contamination, including fossil-fueled power plants, cement production (in which the lime raw material often contains trace mercury), the extraction and processing of primary raw materials such as iron and steel, ferromanganese, zinc, gold and other non-ferrous metals and the processing of secondary raw materials such as iron and steel scrap. Existing control technologies that reduce SO_2, NO_x and PM for coal-fired boilers and incinerators, while not yet widely used in many countries, also yield some level of mercury control. For coal-fired boilers, reductions range from 0 to 96 percent, depending on coal type, boiler design, and emission control equipment. On average, the lower the coal rank, the lower the mercury reductions; however, reductions may also vary within a given coal rank. Technology for additional mercury control is under development and demonstration, but is not commercially deployed. In the long run, integrated control strategies that target multiple pollutants including SO_2, NO_x, PM and mercury may be a cost-effective approach. However, end-of-pipe control technologies, while mitigating the problem of atmospheric mercury pollution, still result in mercury wastes that are potential sources of future emissions and must be disposed of or reused in an environmentally acceptable manner.

D. Mercury waste management

612. Mercury wastes, including those residues recovered by end-of-pipe technologies, constitute a special category of mercury releases, with the potential to affect populations far from the initial source of the mercury. Mercury waste management, the fourth "control" measure mentioned above, may consist of rendering inert the mercury content of waste, followed by controlled landfill, or it may not treat the waste prior to landfill. In Sweden, the only acceptable disposal of mercury waste now consists of "final storage" of the treated waste deep underground, although some technical aspects of this method are yet to be finalised (see further discussion below).

613. Mercury waste management has become more complex as more mercury is collected from a greater variety of sources, including gas filtering products, sludges from the chlor-alkali industry, ashes,

[18] An ordinary (incandescent) lamp consumes several times more energy for the same lumen output as a fluorescent lamp, and hence results in greater emissions of mercury, assuming most of the energy is produced with fossil fuels. According to the International Association for Energy-Efficient Lighting (IAEEL) Newsletter No. 3 (1993), and Newsletter No's 1 and 4 (1994), the extra energy consumed by an incandescent lamp results in 2.6 times more mercury than an average compact fluorescent lamp with the same light intensity, and up to 12 times more mercury than a low-mercury fluorescent lamp, even assuming all of the mercury in the fluorescent lamp is eventually released. (As noted in the text, the mercury content of fluorescent lamps varies widely.) These figures are based on the American energy mix for production of electricity, comprising 56 percent coal, 9 percent fossil gas, 4 percent oil and 31 percent non-fossil fuels. The European energy mix is similar, but diverges significantly for certain countries such as Norway and Sweden that are much more dependent on hydropower. Recycling energy-efficient lamps further reduces their environmental impact.

slags, and inert mineral residues, as well as used fluorescent tubes, batteries and other products that are often not recycled. Low concentrations of mercury in waste are generally permitted in normal landfills, while some nations only allow waste with higher mercury concentrations to be deposited in landfills that are designed with enhanced release control technologies to limit mercury leaching and evaporation. The cost of acceptable disposal of mercury waste in some countries is such that many producers now investigate whether alternatives exist in which they would not have to produce and deal with mercury waste. Mercury waste management, as it is most commonly done today, in accordance with national and local regulations, increasingly requires long-term oversight and investment. Proper management of mercury wastes is important to reduce releases to the environment, such as those that occur due to spills (i.e. from broken thermometers and manometers) or releases that occur over time due to leakage from certain uses (e.g., auto switches,[19] dental amalgams). In addition, given that there is a market demand for mercury, collection of mercury-containing products for recycling limits the need for new mercury mining.

Emission prevention and control measures

614. As illustrated in Figure 8.1, a well thought-out combination of emission prevention and control measures is an effective way to achieve optimal reduction of mercury releases. If one considers some of the more important sources of anthropogenic mercury releases described in previous chapters, one may see how prevention and control measures might be combined and applied to these sources:

- Mercury emissions from **municipal and medical waste incinerators** may be reduced by separating the small fraction of mercury containing waste before it is combusted. For example, in the USA, free household mercury waste collections have been very successful in turning up significant quantities of mercury-containing products and even jars of elemental mercury. Also, separation programmes have proved successful in the hospital sector and a number of hospitals have pledged to avoid purchasing mercury-containing products through joint industry-NGO-Government programmes. However, separation programmes are sometimes difficult or costly to implement widely, especially when dealing with the general public. In such cases a better long-term solution may be to strongly encourage the substitution of non-mercury products for those containing mercury. As a medium term solution, separation programs may be pursued, and mercury removed from the combustion stack gases. Mercury emissions from medical and municipal waste incineration can be controlled relatively well by addition of a carbon sorbent to existing PM and SO_2 control equipment, however, control is not 100% effective and mercury-containing wastes are generated from the process;
- Mercury emissions from **utility and non-utility boilers**, especially those burning coal, may be effectively addressed through pre-combustion coal cleaning, reducing the quantities of coal consumed through increased energy efficiency, end-of-pipe measures such as stack gas cleaning and/or switching to non-coal fuel sources, if possible. Another potential approach might be the use of coal with a lower mercury content. Coal cleaning and other pre-treatment options can certainly be used for reducing mercury emissions when they are viable and cost-effective. Also, additional mercury capture may be achieved by the introduction of a sorbent prior to existing SO_2 and PM control technologies. These technologies are under development and demonstration, but are not yet commercially deployed. Also, by-products of these processes are potential sources of future emissions and must be disposed of or reused in an environmentally acceptable manner;

[19] At secondary steel mills in the USA where end-of-life automobiles and appliances are processed, the predominant source of mercury is believed to be the components in the automobiles/appliances, not natural impurities. The mercury components of greatest concern are switches. Therefore, either emissions control technologies or effective switch removal/collection programs are necessary to minimize mercury releases. For reference material on this topic, see New Jersey DEP's December 2001 Mercury Task Force Report, and Maine DEP's Plan to Reduce Mercury Releases from Motor Vehicles in Maine, January 2002, available on their websites. It should be noted that some of Europe's secondary steel mills may differ in this regard from other regions due to restrictions on the sale of new cars with mercury switches which became effective in 1993 in Sweden and was followed by automobile manufacturers in other parts of Europe.

- Mercury emissions due to **trace contamination of raw materials or feedstocks** such as in the cement, mining and metallurgical industries may be reduced by end-of-pipe controls, and sometimes by selecting a raw material or feedstock with lower trace contamination, if possible.
- Mercury emissions during **scrap steel production**, scrap yards, shredders and secondary steel production, result primarily from convenience light and anti-lock brake system (ABS) switches in motor vehicles; therefore a solution may include effective switch removal/collection programmes;
- Mercury releases and health hazards from **artisanal gold mining** activities may be reduced by educating the miners and their families about hazards, by promoting certain techniques that are safer and that use less or no mercury and, where feasible, by putting in place facilities where the miners can take concentrated ores for the final refining process. Some countries have tried banning the use of mercury by artisanal miners, which may serve to encourage their use of central processing facilities, for example, but enforcement of such a ban can be difficult;
- Mercury releases and occupational exposures during **chlor-alkali production** may be substantially reduced through strict mercury accounting procedures, "good housekeeping" measures to keep mercury from being dispersed, properly filtering exhaust air from the facility and careful handling and proper disposal of mercury wastes. There are a number of specific prevention methods to reduce mercury emissions to the atmosphere. The US chlor-alkali industry invented the use of ultraviolet lights to reveal mercury vapour leaks from production equipment, so that they could be plugged. Equipment is allowed to cool before it is opened, reducing mercury emissions to the atmosphere. A continuous mercury vapour analyser can be employed to detect mercury vapour leaks and to alert workers so that they can take remedial measures. The generally accepted long-term solution is to encourage the orderly phase-out of chlor-alkali production processes that require mercury, and their substitution with technologies that are mercury free;
- Mercury releases and exposures related to mercury-containing **paints, soaps, various switch applications, thermostats, thermometers, manometers, and barometers**, as well as **contact lens solutions, pharmaceuticals and cosmetics** may be reduced by substituting these products with non-mercury products;
- Mercury releases from **dental practices** may be reduced by preparing mercury amalgams more efficiently, by substituting other materials for mercury amalgams, and by installing appropriate traps in the wastewater system;
- Mercury emissions from dental amalgams during **cremation** may only be reduced by removing the amalgams before cremation, which is not a common practice, or by filtering the gaseous emissions when the practice takes place in a crematorium. Since a flue gas cleaner is an expensive control technique for a crematorium, there might be a strong argument for prevention by substituting other materials for mercury amalgams during normal dental care;
- In cases of **uncontrolled disposal of mercury containing products or wastes**, possible reductions in releases from such practises might be obtained by making these practices illegal and adequately enforcing the law, by enhancing access to hazardous waste facilities, and, over the longer term, by reducing the quantities of mercury involved through a range of measures encouraging the substitution of non-mercury products and processes.

615. When one considers the broad range of restrictions and controls increasingly applied to mercury products and processes as summarized in table 8.1 below and the large (and increasing) resources required to adequately monitor and enforce these measures, one better understands a statement by the Japanese Ministry of Environment (JME, 1997), looking back on the Minamata disaster, and Japan's difficulty in recovering from that experience:

> *"From the purely economic standpoint, too, a large amount of cost and a great deal of time are required to deal with such damages, and, when we compare these costs incurred vs. the cost of the measures that could have prevented the pollution, allowing such pollution is certainly not an economically advisable option."*

Table 8.1. Possible restrictions and controls on mercury (adapted from the submission from the Nordic Council of Ministers, sub84gov)

Mercury production, use and control restrictions in place in various countries
• Prevent or limit the intentional use of mercury in processes • Prevent or limit mercury from industrial processes (such as chlor-alkali and metallurgic industry) from being released directly to the environment • Apply emission control technologies to limit emissions of mercury from combustion of fossil fuels and processing of mineral materials • Prevent or limit the release of mercury from processes to the wastewater treatment system • Prevent or limit use of obsolete technology and/or require use of best available technology to reduce or prevent mercury releases • Prevent or limit products containing mercury from being marketed nationally • Prevent products containing mercury from being exported • Prevent or limit the use of already purchased mercury and mercury-containing products • Limit the allowable content of mercury present as impurities in high-volume materials (packaging, etc) • Limit the allowable content of mercury in commercial foodstuffs, particularly fish, and provide guidance (based on same or other limits values) regarding consumption of contaminated fish
Mercury disposal restrictions in place in various countries
• Prevent mercury in products and process waste from being released directly to the environment, by efficient waste collection • Prevent mercury in products and process waste from being mixed with less hazardous waste in the general waste stream, by separate collection and treatment • Prevent or limit mercury releases to the environment from treatment of household waste, hazardous waste and medical waste by emission control technologies • Set limit values for the allowable mercury content in sewage sludge spread on agricultural land • Restrict the use of solid incineration residues in road-building, construction and other applications • Prevent the re-marketing of used, recycled mercury
Mercury control options under consideration
• Prevent or limit the dedicated mining of virgin mercury from the Earth's crust • Prevent or limit the marketing of mercury recovered as a by-product from other mineral or fossil fuel extraction (such as non-ferrous mining activities and natural gas cleaning) • Control trade of pure mercury in order to restrict it to pre-defined essential uses and secure environmentally safe handling (similar to procedures for hazardous waste) • Limit the allowable content of mercury present as impurities in fuels and other bulk mineral materials

8.2 Substitution

616. As described in chapter 6, the deliberate use of mercury in products and processes comprises a significant contribution to the mobilisation and release of mercury to the environment. As the general awareness of mercury's adverse effects on human health and the environment has increased, a number of countries have made special efforts to address mercury in these applications, and have had particular success in reducing mercury use. Canada, Denmark, Norway, Sweden and the USA, among others, have seen the number of applications as well as the quantities of mercury used per application decrease significantly, particularly during the last 15-20 years. Nevertheless, since many mercury-containing products have long technical lives, it should be kept in mind that even if a country decides to ban the marketing and use of mercury in most products, it may take decades before most of the mercury in use is collected and removed from human circulation.

617. Today, alternatives are commercially available for virtually all applications of mercury, permitting a near-total phase-out of mercury use in countries that pursue such an objective. However, the Swedish and Danish experiences demonstrate that the public authorities must have a firm commitment and a clear strategy in place. During the implementation of the Swedish ban on mercury in products (except those few products with an exemption), an investigation of substitutes for mercury-containing measuring instruments and electrical components was carried out. It was discovered that while several applications of mercury were being phased out, some new applications, surprisingly, were appearing - as in electronic equipment - even though alternative technologies were available. It was determined that users of mercury-containing products are faced with four main obstacles to the use of viable alternatives. These include:

- The need for developing and testing efforts, e.g. required for security reasons;
- Higher costs and competition;
- Attitudes to, and knowledge of, alternative techniques – even among equipment suppliers;
- Internationally standardised measurements.

618. These are not insurmountable obstacles, but they may require an appropriate programme of information and incentives. A summary of common mercury products and substitutes is provided in table 8.2 below. Because it is only representative of the great range of mercury applications, this table does not attempt to include all mercury applications or all substitutes. Further information may be found in the references, especially the submission from the Nordic Council of Ministers (sub84gov).

Table 8.2 Summary of alternatives to principle mercury uses, with some indications of relative cost (see notes below table).

Product or application	Alternative(s)	General cost relative to mercury technology
Use of the mercury cell process for producing chlorine, alkali, sodium hydroxide, potassium hydroxide, commonly referred to as chlor-alkali	Best Available Technology (BAT) for the production of chlor-alkali is considered to be membrane technology. Non-asbestos diaphragm technology can also be considered as BAT.	Capital investment costs for conversion to the other processes are significant, but electricity and raw material costs (together comprising about half of total operating costs) for the membrane process, as well as waste treatment and disposal costs, are lower than for the mercury cell process. EIPPCB (2000)¨, US EPA (1993), Submission from the Nordic Council of Ministers, Lindley (1997)
Dental amalgam	As a result of technological advances in recent years, various newer alternatives (cold silver, gallium, ceramic, porcelain, polymers, composites, glass ionomers, etc.) to mercury amalgam fillings are commercially available. However, the Danish National Board of Health does not deem the alternatives fully capable of substituting mercury amalgam in all cases (e.g. fillings in adult molars), and this is also the current Swedish position. Even the viable alternatives are not yet widely known or accepted in many countries, as practitioners generally find it easier to continue using the techniques with which they are most familiar.	Some alternatives are less expensive and some are more expensive than mercury amalgams, some are as easy to apply and others are more difficult, but none of the alternatives require the specialized wastewater treatment equipment that dental professionals need to meet environmental regulations in many countries. KEMI (1998), Submission from the Nordic Council of Ministers, Gustafsson (2001), US EPA (1997)
Mercuric-oxide and mercury-zinc (medical) "button cell" batteries	Virtually mercury-free zinc-air batteries and other button-cell alternatives (actually still containing less than 10 mg of mercury) have been available for several years. Many manufacturers no longer produce mercuric-oxide and mercury-zinc batteries, but they remain a significant problem in the municipal waste stream of most countries.	The cost of alternatives may often be higher than the mercuric-oxide and mercury-zinc batteries, but municipalities can avoid expensive collection and disposal schemes.

Product or application	Alternative(s)	General cost relative to mercury technology
Other batteries	Virtually all other batteries are now available in standard and rechargeable mercury- and cadmium-free versions. Only the older battery manufacturing facilities may continue to produce batteries using the previous techniques and materials.	While comparisons are difficult across a broad range of batteries (and as battery capacities increase), standard mercury-free batteries generally cost about the same as the batteries they replace. Rechargeable batteries, on the other hand, especially the cadmium-free rechargeables, are significantly more expensive to purchase, although they become relatively less expensive if recharged more than 10 or 15 times.
Medical thermometers	There are many alternatives to clinical mercury-thermometers, including electrical and electronic thermometers, “disposables” designed for a single use, glass thermometers containing a Ga/In/Sn “alloy”, etc.	Used mostly for measuring body temperature, electronic thermometers have become standard in Denmark and other countries. While they remain somewhat more expensive than glass mercury thermometers, their price has come down substantially in recent years. Other alternatives are also more expensive, although the recently introduced Ga/In/Sn thermometer should approach the cost of old mercury thermometers over time.
Other thermometers	Non-medical thermometers are used very widely. Alternatives to mercury as the measuring medium include other liquids, gas, electrical and electronic (probably the most common) sensors. The choice of alternative depends on the temperature range, the specific application, and the need for precision. (Mercury thermometers are worthless at temperatures below –39°C, when mercury turns solid) For temperature readings in buildings, a bimetal device is often used, or a Pt-100 or thermocouple is used when a temperature signal needs to be transferred to a controller or recorder. Electronic alternatives have several advantages over mercury. One thermometer can be adjusted to several different measuring ranges, thereby substituting for several mercury thermometers. Further, it is possible to read temperatures digitally and record them remotely. This could reduce the chance of human error, as well as reduce operating costs. For a very small number of precision applications, mercury thermometers are still preferred for technical reasons, e.g. for calibration of other thermometer types, for international standards, etc..	There is such a great range of mercury alternatives and applications that it can only be said that prices of alternatives vary widely, but are not necessarily more expensive. It should also be noted that, while the initial cost of a mercury glass thermometer is lower than an electronic device, the frequency of broken mercury thermometers is higher, and one electronic thermometer may replace several mercury ones. If an annual cost is calculated, the price of an electronic measuring device is probably no higher than the mercury device it replaces. Gustafsson (1997), Submission from the Nordic Council of Ministers, Rasmussen (1992)
Laboratory use of mercury	It is entirely possible to restrict mercury use in school or university laboratories to a few specific, controllable uses (mainly references and standard reagents).	This initiative has already been implemented in Swedish and Danish legislation. The alternatives are generally no more expensive, and the need for control of mercury sources in the laboratory is greatly reduced.
Pesticides and biocides for different products and processes.	The use of mercury in pesticides and biocides has been discontinued or banned in many countries. Two main alternatives have been promoted in their place: 1) Use of processes not requiring chemical pesticides/biocides, and 2) Easily degradable, narrow-targeted substances with minimal environmental impact.	These alternatives are in place in many countries. The range of products and applications is too diverse to make definitive statements about cost comparisons, although it is likely that in the majority of cases costs are roughly comparable, and environmental benefits are considerable.

<table>
<tr><th>Product or application</th><th>Alternative(s)</th><th>General cost relative to mercury technology</th></tr>
<tr><td>Pressure measuring and control equipment</td><td>Mercury is used as a "heavy liquid" in pressure gauges, pressure switches and pressure transmitters. All of these may be substituted without any loss of accuracy or reliability. Three main technologies are used:
• flexible membranes,
• piezoelectric crystals and other sensors that change some physical property when the pressure changes, and
• fiber-optic pressure sensors, based on light transmission.
In pressure gauges like U-tube meters, barometers, and manometers, mercury is used to continuously indicate pressure differentials. Here, mercury can be replaced by another liquid, by gas or by other techniques.
Mercury pressure switches are used to measure pressure or vacuum differentials. They can be replaced by the same alternatives as for pressure gauges, but also equipped with a non-mercury breaker switch.
For remote transmission of measurement readings, a pressure transmitter is often used. A special mercury transmitter is a circular tube which may contain up to 8 kg of mercury. Alternatives use a potentiometer or a differential transformer to measure pressure changes and transmit an electronic signal. The most common alternative device is a diaphragm sensor.</td><td>
Alternatives based on gas, other liquids or a mechanical spring show no significant differences in price, compared to mercury devices. Alternatives in the form of electric and electronic instruments are only slightly more expensive, but have several advantages over mercury.
Gustafsson (2001), Rasmussen (1992), Submission from the Nordic Council of Ministers.</td></tr>
<tr><td>Electrical and electronic components</td><td>With very few exceptions, there are no technical obstacles to replacing electrical components, conventional relays and other contacts (even when these are contained in level switches, pressure switches, thermostats, etc.) with equivalent mercury-free components. A number of examples are given below.</td><td rowspan="2">
There are no significant price differences between conventional mercury and mercury-free relays and contacts, except for very specific applications. There are also examples of mercury components, which are more expensive than the alternatives.
Gustafsson (1997).</td></tr>
<tr><td colspan="2">
<table>
<tr><th>Mercury component</th><th>Alternative component</th><th>Application</th></tr>
<tr><td>Tilt-switch – silent switch</td><td>Various, e.g. manual/mechanical (rolling steel ball, alternative conducting fluid), micro-switch</td><td>Circuit control, thermostats, communications</td></tr>
<tr><td>Electronic-switch</td><td>Solid state-switch, optical switch</td><td>Circuit control, thermostats, communications</td></tr>
<tr><td>Reed-switch – "mercury-wetted"</td><td>Solid-state-switch, electro-optical-switch, semiconductor</td><td>Communications, circuit control in sensitive electronic devices</td></tr>
<tr><td>Proximity sensor/switch – "non-touch-contact"</td><td>inductive sensor
capacitive sensor
photoelectric sensor
ultrasonic</td><td>shaft rotation, conveyors
conveyors
conveyors
conveyors</td></tr>
</table>
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</table>

Product or application	Alternative(s)	General cost relative to mercury technology
Energy-efficient lamps	Currently, there are no mercury-free energy-efficient alternatives to the energy-efficient lamps on the market, although there are reports of a high-efficiency non-mercury lamp based on the field-emission effect, which is said to be starting production in China[20], and a lamp based on diode technology is in research. One can only prescribe production/use of energy-efficient lamps with a minimum mercury-content, and collection and treatment of spent lamps. According to European Commission Decision 1999/568/EC (amended 9 September 2002), for a manufacturer to be allowed to use the European Ecolabel on a single-ended compact fluorescent lamp, the mercury content must not exceed 4 mg, and the life of the lamp must exceed 10,000 hours. Other mercury-containing light sources exist, mainly for special, limited purposes and sold in much lower quantities, although recently introduced and fashionable auto headlamps containing mercury are a particular concern, as they are inconvenient to recover and recycle, and perfectly acceptable non-mercury alternatives are available.	 Low-mercury lamps are slightly more expensive than those with a bit more mercury. Incandescent and some other alternative lamps are less expensive than energy-efficient lamps, but they have a much higher energy/operating cost. Falk (1994), Gustafsson (1997), Submission from the Nordic Council of Ministers.
Artisanal gold extraction	One alternative that seems to offer promise is a non-mercury electrolytic process (see section 8.5.3) started in Brazil. However, it has been in existence for some 10 years and does not seem to have convinced the artisanal community. An alternative is a cyanidation process, which is reportedly used by many relatively small-scale miners in Mexico and some elsewhere, despite the fact that it requires greater investments and greater process skills, and carries its own hazards. Another option is the Minataur process developed in South Africa by the government's mineral technology research body, Mintek. This involves treating the ore with hydrochloric acid in the presence of sodium hypochlorite and then using sodium metabisulphate or oxalic acid to precipitate the gold out as a concentrate that is 99.5% fine gold powder. UNIDO's approach in addressing this problem is to encourage the substitution of low recovery, high mercury consuming and discharging processes with environmentally safe and high-yield gold extraction alternatives that sharply reduce or eliminate the use and discharge of mercury. Depending upon the technique, cost and delivery method, some proposals are better received than others, but none as yet have been widely adopted. A typical technique, developed by Imperial College Consultants (ICON), London, uses substantially less mercury and has demonstrated a 40-50 % better gold recovery efficiency.	 The economics of these alternatives have not been investigated in detail here, but indications (the first process used on a wide scale, and the second delivering more gold and using less mercury) are that they are no more expensive than the traditional mercury process. If they were, they would not be adopted by the garimpeiros. CETEM/IMAAC/CYTED (2001), ICON (2000), UNIDO (1997), UNIDO (2000), MMSD (2002)

Note: The coloured bar is an indicator of the overall user/consumer price level for mercury-free alternatives as compared to mercury technology. Price-determining factors vary among the uses (expenses for purchase, use, maintenance etc.), but do not include external costs.

Green (left) = lower cost alternative,
Orange (centre) = similar cost
Red (right) = higher cost.

[20] See http://www.lightlab.se/english/products/index.htm.

8.2.1 Denmark's experience

619. A good example of the potential achievements of a coherent substitution strategy is evident from the experience of Denmark. In recent years Denmark decided to strongly encourage substitutes for mercury products, including placing a ban on the sale and use of most mercury products. As in a number of other countries, a substantial decrease in mercury consumption for intentional uses has been observed. As can be seen in table 8.3, during the period 1983-1993 the annual consumption of mercury in intentional uses fell from about 16 metric tons in 1982/83 to 6 metric tons in 1992/93, and decreased further to 1.5 metric tons in 2000/2001. In the same period, releases to the environment were reduced from an estimated 6.9-9.9 metric tons in 1983, to 2.3-3.0 tons in 1993 (of which 0.3-0.8 tons originated from trace amounts of mercury in fuels and minerals). The deposits in (controlled) landfills have increased during the same period from 1.7-2.9 metric tons to 2.3-4.5 tons, most likely as a result of increased hazardous waste collection (reflecting the mercury content of used products, batteries, etc.) and improved filtering of waste incinerator emissions.

Table 8.3 Estimated changes in annual consumption of mercury in Denmark (metric tons/year). Ref. Submission from the Nordic Council of Ministers (sub84gov), based on Maag et al. *(1996), Hansen (1985) and Heron (2001).*

Danish national consumption of mercury	Year/use	1982/83	1992/93	2000/2001
	Chlor-alkali production (discontinued in 1997)	3.00	2.50	0
	Dental amalgam	3.1	1.80	0.9
	Mercury-oxide batteries	2.40	0.36	0
	Other batteries	2.30	0.28	~ 0
	Measuring and control equipment	0.53	0.50	0.3
	Electric and electronic switches	0.34	0.30	~ 0
	Light sources (lamps)	0.14	0.17	0.17
	Medical thermometers	0.75	0.05	0
	Other thermometers	1.55	0.10	0
	Laboratory chemicals	0.50	0.09	0.09
	Other intentional uses	1.48	0.03	0.03
	Sub-total, intentional uses	16.09	6.18	1.5
	Impurities in consumed fuels, minerals and high-volume materials (non-intentional mobilisation)	1.96	1.80	1.8
	Total	18.05	7.98	3.3

Note: Shading indicates graphically the approx. change in quantities of mercury consumed over time.

8.2.2 Need for further development of substitutes

620. For a very few applications, representing a relatively small amount of mercury consumption, more research and development is needed in order to be able to completely eliminate mercury use (submission from the Nordic Council of Ministers, sub84gov).

Fluorescent lamps

621. For mercury use in fluorescent lamps, which are known for their low energy consumption, no commercially mature alternatives are yet available. Work has been done, however, to reduce the amount of mercury needed in each lamp. From typical amounts of 20-40 mg of mercury per lamp, lamps with only 3 mg of mercury are commercially available today. Unfortunately these modern low-mercury lamps have difficulty in competing on price with the higher-mercury lamps, and consumers are generally unaware of the difference between them.

622. The use of diodes as lights – recently installed in some traffic lights - has been proposed as an energy-efficient substitute. The strength of the light source for this application would appear to be comparable to what is needed for some housing purposes. However, until mercury-free alternatives are widely deployed, the mercury in fluorescent lamps may be managed by collection of used lamps and recycling or proper waste treatment. This has been attempted in a few countries and localities, but it has been difficult in most cases to achieve significant collection rates.

Dental amalgam

623. As mentioned in chapter 6, mercury amalgam fillings contribute significantly to the human (metallic) mercury burden. While there has been substantial developmental work on a range of alternatives, there is not yet a consensus that substitutes can adequately replace mercury amalgams in all dental applications. In Sweden and Denmark voluntary substitution agreements have been in place for a number of years and the consumption of mercury for dental use has decreased significantly. In Denmark mercury amalgams are permitted (until further notice) only in molars where the fillings are worn.

Chemical standard analyses

624. A number of traditionally important chemical standard analyses involve the use of mercury compounds. While mercury-free substitutes are generally available, this issue is mentioned here because it may take time to change standards previously agreed upon. For example, a common analysis using mercury is the COD (chemical oxygen demand - measuring contents of organic matter) analysis, which is widely used to control and monitor the quality of wastewater. Other oxygen demand (e.g., the so-called BOD – biological oxygen demand) analyses are available and are often used. However, the problem is that the prescriptions of many mandatory analyses in regulations and individual wastewater release permits specify the COD analysis, and need to be changed. This is possible, but requires attention and time. The Swedish government is considering a ban on mercury use in chemicals for analyses and reagents from 1 January 2004.

8.3 Reducing mercury releases

625. Processing of mineral resources at high temperatures, such as combustion of fossil fuels, roasting and smelting of ores, kiln operations in the cement industry, as well as incineration of wastes and production of certain chemicals, results in the release of a number of volatile trace elements into the atmosphere.

626. It is often believed that a combustion unit – typically used for power generation or waste incineration – with an emission control device removes most or all of the mercury and other heavy metals emitted during combustion. However, unlike other heavy metals, mercury has special properties as described in chapter 6, that make it difficult to capture in many control devices. While some units with control devices do remove mercury quite effectively,[21] there are likely tens of thousands of combustion units around the world with no flue gas cleaning devices at all, or where such devices are not effective in removing mercury.

627. While this section is focused on mercury emissions to the atmosphere, it should be remembered that mercury is a persistent pollutant that also cycles through other environmental media (e.g., water and soil). Further, it should be kept in mind that mercury that is captured in a pollution control device or diverted from an incinerator may still be released to the environment unless the slags or residues are properly managed.

628. Significant parts of the descriptive text in sections 8.3.1 through 8.3.4 below have been based on Pacyna and Pacyna (2000).

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[21] Based on data gathered by US EPA in 1999 on mercury emissions from electric utilities, control device efficiencies, and other information, mercury emission reductions effected by current controls for other pollutants ranged from 0 to over 90 percent. In the USA, many waste incineration units with control devices are achieving even higher levels of mercury control.

8.3.1 Nature of mercury emissions

629. In order to fully appreciate the relevance of various emission control technologies, it is first necessary to review the context of these mercury emissions (Pacyna and Pacyna, 2000, as modified by US comments to an earlier draft of this report).

- Concentrations of mercury in coals and fuel oils vary substantially depending on the type of fuel and its origin. The mercury in coal may be associated with the organic or the inorganic constituents (mineral matter) of coal. When it is associated with mineral matter such as sulfides it can often be removed by physical coal cleaning techniques. The removal of mercury from the organic fraction of coal is much more difficult and costly.
- Most of the processes generating atmospheric emissions of mercury employ high temperature. During these processes, including combustion of fossil fuels, incineration of wastes, roasting and smelting operations in non-ferrous and ferrous metallurgy, and cement production, mercury introduced with input material volatilizes and is converted to elemental mercury (Hg^0) in the high temperature region of the process. As the flue gas is cooled to flue gas cleaning temperatures the mercury may remain as Hg^0 or part of it may be oxidized to ionic mercury [Hg(II)]. Further, Hg^0 and/or Hg(II) may be adsorbed onto particles to form particle-bound mercury [Hg(p)]. The relative magnitude of Hg^0, Hg(II), and Hg(p) in flue gas is called the speciation of mercury.
- Mercury oxidization can result from gas-phase or gas-solid reactions (heterogeneous reactions). Laboratory experiments and thermal-chemical studies have implicated atomic chlorine (Cl^-) and nitrogen oxide (NO_2) as two potential oxidizing agents. Thermal-chemical equilibrium studies indicate that the preferred oxidation product is $HgCl_2$ when sufficient chlorine is present in the fuel or waste (i.e., when the concentration of chlorine is substantially higher than the concentration of mercury in the flue gas). Fly ash and other surfaces within the combustion system can catalyze or mediate mercury oxidization reactions. Major factors that affect mercury speciation are the fuel (or waste) composition, the combustion conditions, and the type of flue gas cleaning methods used.
- Various technologies within the same industry may generate different amounts of atmospheric emissions of mercury. It can be generalized for conventional thermal power plants that the plant design, particularly the burner configuration, fly ash characteristics, etc., have an impact on the emissions.[22]
- The major parameters that determine the amount and characteristics of mercury emitted to the atmosphere from high-temperature processes are the amount and speciation of mercury entering the flue gas cleaning devices, the type of flue gas cleaning devices used, the concentrations of other constituents (chlorine, NO_x), and the temperature at which the flue gas cleaning devices are operated.

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[22] Cyclone- and pulverized coal- (PC) fired boilers both operate at temperatures that volatilise the mercury in coal and convert it to Hg^0 in the high-temperature regions of the furnace. The difference in stack emissions of mercury from these two types of units is probably due to the amount and characteristics of fly ash. In cyclone-fired units most of the mineral matter is converted to slag, which is removed in a molten form in the bottom of the combustion unit. A relatively small amount of the mineral matter is converted to fly ash, which in turn contains a relatively small amount of unburned carbon. In PC-fired boilers, approximately 90 percent of the coal mineral matter is converted to fly ash. The use of low- NO_x burners tends to increase the amount of carbon in fly ash, increasing the amount of mercury that is adsorbed and subsequently captured as Hg(p) in a downstream electrostatic precipitator (ESP) or fabric filter (FF).

A similar phenomenon has been observed in systems that burn municipal solid waste. Some mass-burn-water-wall incinerators exhibit very good combustion and low fly ash carbon concentrations. Well operated mass-burn units equipped with spray dryer and fabric filters (SD/FFs) exhibit little if any mercury capture. Alternatively, US tests on one refuse-derived-fuel (RDF) combustor equipped with a SD/FF exhibited mercury captures ranging from 96 to 99 percent. In a similar fashion, fluidized bed incinerators typically emit relatively large amounts of fly ash with a high carbon content. While improved mercury capture by fly ash sometimes correlates with low NO_x emission, there does not appear to be a cause and effect relationship between the flue gas concentration of NO_x and mercury capture.

8.3.2 Available options

630. The options available for reducing mercury releases from various processes may be organized in two categories: non-control-technology options, and control-technology options.

631. The best-known **non-control-technology options** include such measures as:

- Conversion to natural gas, oil, or a non-fossil power generating technology;
- Improved energy efficiency (reductions of CO_2-emissions as foreseen in the Kyoto Protocol to the UN Framework Convention on Climate Change are expected to help reduce mercury emissions from fossil fuel power generation);
- Banning mercury in products;
- Taxes or other disincentives to the use of mercury in products; and
- Product labeling.

632. Banning and taxes are reasonably self-explanatory. Product labelling has advantages and disadvantages, but has proven rather effective in some cases, in combination with other measures. For example, in the case of consumer batteries, consumers paid significant attention to labels concerning the content of mercury and cadmium.

633. **Control-technology options** for reducing releases may be thought of in the following three categories, which are further elaborated in the next section:

A. Pre-treatment measures;
B. Combustion modifications; and
C. Flue gas cleaning or end-of-pipe controls.

634. It should be noted that the descriptions of techniques and technologies for emission reductions that follow are general, and not intended to prescribe methods or equipment that should be used to control mercury releases from any specific site or plant. The ultimate appropriateness and effectiveness of any given technique or technology is site specific, and needs to take into consideration local circumstances.

8.3.3 Reducing mercury emissions from utility and non-utility boilers and incinerators[23]

A. Pre-treatment measures

635. **Pre-treatment** measures typically include coal washing, hand-sorting of waste at an incinerator or disposal site, the production of refuse-derived fuel at an incinerator site, or the separation of waste at a material recycling and handling facility.

B. Combustion modifications

636. **Combustion modifications** act to change the combustion process. These modifications may be used to reduce mercury concentrations in the process flue gas, or they may be used to change the characteristics of the flue gas stream so that mercury is more easily captured in downstream flue gas cleaning equipment. The modifications may include using technologies such as fluidized bed combustor, mass burn/waterwall combustor, low-NO_x burner, etc.

637. As an example, combustion modification-based low-NO_x technologies should reduce mercury emissions in the exhaust gases due to lower operating temperatures, although very limited information on this technology makes it difficult to draw firm conclusions. While some sources indicate that a reasonable reduction can be achieved, other preliminary results of staged combustion in atmospheric fluidized bed combustion (AFBC) units indicated that low-NO_x had little effect on trace element emissions.

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[23] For considerably more detail about recent US developments in this field, the reader is invited to consult US EPA (1998), Brown *et al*. (1999) and US EPA (2002).

638. Switching to the same type of fuel, but with lower mercury content, which does not involve pre-treatment, may also be considered a combustion modification.

639. Other examples of modifications that can potentially be used to improve capture of mercury are combustion modification techniques that increase the carbon content and subsequent mercury adsorption capacity of fly ash. Increased fly ash carbon content occurs during the use of low-NO_x burners or the use of a NO_x control technology called reburning. This results from fuel-rich regions within the combustion system. While increased mercury capture has been shown to occur with increased fly ash carbon, this phenomenon has not been used in commercial practice for the control of mercury emissions, and it should be considered a potential control option that might be available in the future.

C. Flue gas treatment (end-of-pipe) controls

640. **Flue gas treatment, or end-of-pipe, controls** are currently deployed for control of SO_2, NO_x, and PM: SO_2 controls include a variety of wet and dry scrubbers; NO_x may be controlled by selective catalytic or selective non-catalytic reduction; and PM may be controlled by fabric filters (FFs) or electrostatic precipitators (ESPs). There has been extensive testing of the mercury removable capabilities of these systems on a wide range of coal-fired utility boilers in the USA. The average results ranged from 0 to 96 percent dependent on a variety of factors as described in detail below. Generally speaking:

- A specific technology, or combination of technologies, produced a range of mercury reduction for any coal type;
- The type of coal strongly affected the mercury control achieved, with average percent removal increasing as coal "rank" increased from lignite through subbituminous to bituminous. Within any given rank, a range of removals was achieved. Note also that world coals represent a wider range of coal rank (e.g. brown coal) and characteristics (e.g. sulfur, ash) than US coals.

641. Additional mercury control can be achieved by injection of a sorbent (carbon- and/or calcium-based) prior to the flue gas treatment system. These technologies are currently under development and demonstration in the USA, but are not yet commercially deployed.

642. Research so far has indicated that the most cost-effective approach to mercury control may be an integrated multipollutant (SO_2, NO_x, PM, and mercury) control technology. A number of these technologies are in the pilot-scale development stage in the USA, but have generally not yet been demonstrated at full-scale. Recent Swedish experience has demonstrated the economic as well as technical efficiency of such systems in full-scale waste incinerators and utility burners (Hylander *et al.*, 2002, as cited in comments from Uppsala University, Sweden).

643. The potential impact of mercury control technology on by-product utilization and/or disposal needs to be evaluated. For example, increased mercury concentration in the gypsum collected in flue-gas scrubbers may exceed the level permitted in wallboard; or an increased carbon content in the by-product may limit its use in aggregate used for road surfacing. Furthermore, any by-product must be in a stable form for disposal if it cannot be utilized. Either of these potential impacts would affect the cost-effectiveness of the process.

644. The major mercury capture mechanisms include the adsorption of mercury onto solid surfaces and the solvation of mercury in liquid scrubbers. Mercury can be adsorbed onto fly ash or entrained sorbent particles for subsequent capture in particulate matter (PM) control devices. Mercury can also be captured in packed beds containing a variety of sorbents.

645. Distribution of mercury within the various streams of wet flue gas desulfurisation (FGD) systems has been studied in a number of countries. These studies have shown that mercury capture in wet FGD systems depends on the rank of coal burned, and the design and operating conditions of the FGD system. Wet FGD scrubbers were generally preceded by PM control devices (i.e., ESPs or FFs). The total amount of mercury captured in a boiler equipped with a scrubber depended on the amount of mercury captured in the upstream PM control device and the soluble Hg^{2+} captured by the scrubber. Flue

gas from the exhausts of units burning bituminous coals exhibited higher levels of Hg^{2+} than flue gas from burning of lower rank coals; this mercury was readily captured in the PM control device and downstream scrubber. Mercury in the exhausts of units burning low rank coals tended to be Hg^0, and mercury capture in these units tended to be minimal. The scrubber chemistry must also be controlled to insure that Hg^{2+} that is dissolved in the scrubber liquor is not converted back to Hg^0 and re-entrained in the flue gas. Scrubber sludges must also be handled in an environmentally acceptable manner.

646. Pacyna reported that some wet FGD systems are unable to remove more than 30 percent of the mercury in the flue gas, but in general the removal efficiency ranges from 30 to 50 percent (Pacyna and Pacyna, 2000). Short-term tests in the USA have exhibited emission reductions for units firing bituminous coals that range from 40 to 95 percent. The best capture was found for a unit equipped with a FF and a wet limestone (a type of FGD) scrubber.

647. Soluble forms of mercury can be captured in wet scrubbers. Soluble forms of mercury include mercuric chloride [$Hg(Cl_2)$] and other ionic forms of mercury. Hg^0 is relatively insoluble in aqueous solutions and it must either be adsorbed onto a solid, or it must be oxidized to an ionic form that can be captured by scrubbing. Wet FGD systems used on units burning bituminous coal (which emit relatively more of the water soluble ionic mercury) perform much better than do such systems on units burning subbituminous coal (which emit relatively more non-soluble elemental mercury).

648. Major factors that affect mercury speciation are the fuel (or waste) composition, the combustion conditions, and the type of flue gas cleaning methods used. Coal rank and chlorine content are extremely important factors in the speciation and capture of mercury with different types of air pollution control technologies. In the USA, bituminous coals tend to have relatively high concentrations of chlorine (Cl). This can result in the oxidization of Hg^0 to Hg^{2+} (primarily $HgCl_2$). The Hg^{2+} can be adsorbed onto fly ash carbon and captured in an ESP or FF. Bituminous pulverized-coal (PC) fired boilers equipped with an ESP or FF may exhibit total mercury captures ranging from 20 percent to more than 90 percent. The higher levels of capture are believed to be associated with a higher fly ash carbon content. However, carbon in fly ash can negatively impact its use as a by-product in concrete, as well as negatively impact plant heat rate. Units that burn bituminous coal, and that are equipped with dry flue gas desulfurization (FGD) scrubbers or wet FGD scrubbers, also exhibit high levels of mercury capture. In contrast, low rank US coals (subbituminous coal and lignite) are alkaline, have a relatively low chlorine content, and have fly ash with a low carbon content. Mercury in the exhausts of plants burning low rank coals tends to be predominately Hg^0. The capture of mercury from the flue gas from these plants tends to be low, whether the units are equipped with an ESP, FF, dry FGD scrubber, or wet FGD scrubber.

649. Conventional mercury measurement methods must be carefully performed to effectively determine the critical speciation distribution (i.e., Hg^0/Hg^{2+}). In addition, continuous emission monitors (CEMs), intended to provide a direct determination of either total Hg^0 and/or Hg^0 and Hg^{2+} are currently under development and evaluation in the field.

(1) Wet FGD systems

650. Distribution of mercury within various streams of the wet FGD system was studied in a number of countries. The relatively low temperatures found in wet scrubber systems helped many of the more volatile trace elements to condense from the vapour phase and thus to be removed from the flue gases. Due to the special characteristics of mercury, wet FGD facilities are sometimes unable to remove more than 30 percent of the mercury in exhaust gases. In general, however, removal efficiency for mercury ranges from 30 to 50 percent (Pacyna and Pacyna, 2000).

651. Removal of trace elements from exhaust gases by wet FGD systems has been studied in the Netherlands, where only pulverized coal-fired dry-bottom boilers are used, equipped with a high-efficiency electrostatic precipitator (ESP) and an FGD design that consists of a wet lime/limestone-gypsum process with "prescrubber." Mostly bituminous coals (lower mercury content) imported mainly from the USA and Australia are burnt. In one study the mercury concentration upstream of the

FGD system was 3.4 µg/m^3 and downstream was 1.0 µg/m^3. The relative distribution of mercury among bottom ash, collected pulverised-fuel ash and fly-ash in the flue gases and in the vapour phase was about 10 percent on fine particles and about 90 percent in vapour phase. 87 percent of the mercury content of the coal was released in the flue gases, and up to 70 percent of that was removed by the wet FGD system. About 60 percent of mercury removal takes place in the prescrubber and about 40 percent in the main scrubber. These mercury removal stages are summarized in figure 8.2 below (Pacyna and Pacyna, 2000).

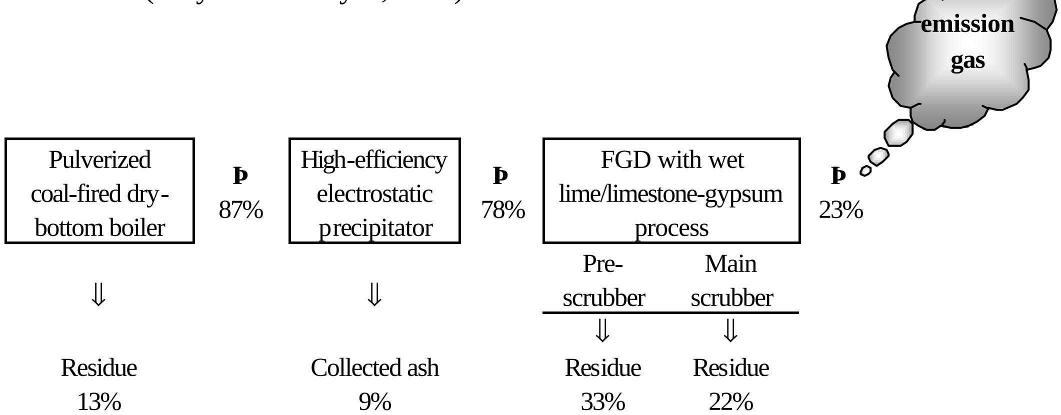

Figure 8.2 Reducing mercury emissions with wet FGD systems

652. Mercury mass balances are difficult to make. They are dependent on equipment configurations and operating conditions used at each individual site. For example, the partitioning of mercury among bottom ash (residue), collected fly ash, scrubber residues, and stack emissions may vary substantially depending on the coal rank, the boiler design, plant operating conditions, and the flue gas cleaning methods used.

(2) Dry FGD systems

653. Retention of vapour phase mercury by spray dryers has been investigated in Scandinavia and the USA for coal combustors and for incinerators. In summary, the overall removal of mercury in various spray dry systems varied from about 35 to 85 percent. The highest removal efficiencies were achieved in spray dry systems fitted with downstream fabric filters (Pacyna and Pacyna, 2000).

(3) Mercury-bearing particle emissions

654. Coal-fired power plants and municipal incinerators are most frequently equipped with either **electrostatic precipitators** (ESPs) or fabric filters. ESPs are particularly efficient in removing all types of particles with diameters larger than 0.01 µm, including those bearing mercury after condensation within exhaust gases. Particles containing trace elements are concentrated mostly in two size ranges: 1) at ca. 0.15 µm diameter and 2) between 2 and 8 µm diameter. Mercury can be found on particles in both size ranges. ESPs can tolerate operating temperatures as high as 720 K (Pacyna and Pacyna, 2000).

655. **Fabric filters** are also used in coal-fired power plants. The particle collection efficiency (not the same as the mercury collection efficiency) is always very high, and even for particles of 0.01 µm diameter, exceeds 99 percent. However, the durability of fabric filters is very dependent upon the working temperature and their resistance to chemical attack by corrosive elements in exhaust gases. The temperature of exhaust gases often exceeds the temperature tolerance for fabric filter material, and therefore limits the application of fabric filters (Pacyna and Pacyna, 2000). According to comments from the US, fabric filters capable of temperatures seen in coal-fired boilers are available in the US.

656. A number of other control technologies and combinations are employed in utility boilers. Table 8.4 summarizes most of the commonly used control technologies for North American utility (electrical generating station) boilers, and their effectiveness at reducing mercury and other polluting emissions,

while table 8.5 provides some more recent measurements of mercury emissions in the USA (US EPA, 2002).

Table 8.4 Control technologies used in North American utility boilers (NEG/ECP, 2000)

Technology	Mercury control effectiveness	Control of other pollutants	Availability and other notes
Selective Non-Catalytic Reduction	Unknown	30-60% NO_x reduction	Available and used on utility boilers. Minor reduced boiler efficiency.
Selective Catalytic Reduction	SCR + wet scrubber combination may result in substantial mercury reduction (see below)	70->90% NO_x reduction	Available and used on larger power plants. Minor reduced boiler efficiency. SCR catalyst may improve oxidation of elemental mercury to divalent mercury, which can be captured in a wet scrubber used for SO_2 control. The ability of SCR to improve the oxidation of Hg for capture in scrubbers may be highly coal-specific.
Low NO_x burners	None	>50% NO_x reduction possible	Available and in use on most coal-fired boilers. SCR and SNCR retrofits provide additional NO_x control beyond low-NO_x burners. It has been postulated that LNBs will improve mercury capture due to the increase in amount of unburned carbon (i.e., carbon loss on ignition [LOI]) in the flue gas stream that may act in a manner similar to activated carbon injection.
Coal Cleaning	0-78%	Average 48% reduction in SO_2 emission potential	Already done on most eastern and mid-western coal to reduce sulfur and improve boiler performance. Mercury removal varies widely, typically from 10% to 50% with mean removal rate of 21%. More advanced coal cleaning methods are under development.
Wet Scrubber	Up to 90% removal of oxidized Hg. No removal of elemental Hg	80->90% SO_2 removal	Already in use to reduce SO_2. Effectiveness for Hg removal highly dependent on mix of chemical species present and on other factors including liquid-to-gas ratio, chlorine content, and coal type.
Combined SCR with Wet Scrubber	>80% removal of overall Hg may be possible for units firing bituminous coals; effectiveness for units firing subbituminous coals is uncertain at this time.	>90% SO_2 and >90% NO_x removal possible	SCR already in use to reduce NO_x. Helps convert elemental Hg to soluble, oxidized form, thereby allowing for greater removal by downstream wet scrubber. Results are based on limited but encouraging data. The ability of SCR to improve the oxidation of Hg for capture in scrubbers may be highly coal-specific.
Dry scrubber with ESP or FF	6-9% reported by NEG/ECP; recent EPA studies reported average removal of approx. 63%)	80-90% SO_2 removal	In use on only 1% of US boilers (most units apply wet scrubbers). Removal efficiency for Hg depends on speciation, temperature, and chlorine content. Lime scrubbers show better Hg removal in pilot tests.
Electrostatic Precipitator (ESP)	0-82% (cold-side ESP) reported by NEG/ECP; EPA found 36% for bituminous and 3% for subitumninous (see Table 8-5)	>99% PM removal	Already in use for particulate removal. Cooler temperature improves ESP performance. US EPA found Hg removal efficiency of 42-83% on oil-fired boilers.
Fabric Filter (baghouse)	0-73% reported by NEG/ECP; EPA found 90% for bituminous and 72% for subbituminous (see Table 8-5)	>99% PM removal	Only filters providing particulate collection efficiencies >99% appear to reduce significant amounts of Hg, but data are limited. Again, lower temperatures appear to improve performance. Baghouses are more effective than ESPs in controlling mercury.
Enhanced ESP	0-50% at one test unit	>99% PM removal	Enhanced ESPs being developed to capture finer particles may remove more Hg. At one test unit Hg removal improved with lower temperature.
Wet ESP	Around 30% in 2 pilot scale studies	56% mean PM removal in pilot studies	Wet ESP being investigated for “polishing” residual emissions from other controls. May improve mercury removal. Lower temperature improves Hg control.
Combined ESP/Baghouse	34-87% in 2 pilot facilities	>99% PM removal	Combination technology to achieve very low PM emissions can improve removal of Hg & other toxics when used in conjunction with powdered activated carbon.

Technology	Mercury control effectiveness	Control of other pollutants	Availability and other notes
Carbon injection	Recent full-scale test results indicate about 80% removal with bituminous coal+ESP+COHPAC and 55-60% with subbituminous coal+ESP	Not applicable	Cost and removal effectiveness are directly related to the amount of carbon used. Used carbon may create a hazardous waste disposal issue. Carbon injection on utility boilers is currently under development and demonstration, but is not yet commercially deployed.
Fuel Switching	>99% for natural gas	>99% SO_2 and PM control; 50-75% NO_x reduction	Fuel switching reduces multiple pollutants, incl. NO_x, SO_2, particulates and CO_2. Accounting for multiple pollutant benefits reduces control costs for mercury alone. Cost affected by several factors, including fuel costs, other pollutant control costs, heat rate, facility age, capacity factor, new plant capital costs and discount rates.

Abbreviations:
SNCR - Selective non-catalytic reduction
SCR - Selective catalytic reduction
LNB - Low-NO_x burner
ESP - Electrostatic precipitator
PM - Particulate matter

Table 8.5 Recent measurements of mercury control technologies in the USA (US EPA, 2002)

Average Mercury Capture by Existing Post-combustion Control Configurations Used for PC-fired Boilers

Post-combustion Control Strategy	Post-combustion Emission Control Device Configuration	Average Mercury Capture by Control Configuration		
		Coal Burned in Pulverized-coal-fired Boiler Unit		
		Bituminous Coal	Subbituminous Coal	Lignite
PM Control Only	CS-ESP	36 %	3 %	-4 %
	HS-ESP	9 %	6 %	Not tested
	FF	90 %	72 %	Not tested
	PS	Not tested	9 %	Not tested
PM Control and Spray Dryer Adsorber	SDA+ESP	Not tested	35 %	Not tested
	SDA+FF	98 %	24 %	0 %
	SDA+FF+SCR	98 %	Not tested	Not tested
PM Control and Wet FGD System (a)	PS+FGD	12 %	-8 %	33 %
	CS-ESP+FGD	74 %	29 %	44 %
	HS-ESP+FGD	50 %	29 %	Not tested
	FF+FGD	98 %	Not tested	Not tested

(a) Estimated capture across both control devices
CS-ESP - Cold-side electrostatic precipitator
FF - Fabric filter
SDA - Spray dryer adsorber system
SCR - Selective catalytic reduction
HS-ESP - Hot-side electrostatic precipitator
PS - Particle scrubber
FGD – Flue gas desulfurization

657. Some control technologies typically serve to reduce emissions of more than one pollutant and, in fact, have been driven for the most part by acid rain emission controls. For example, wet scrubbers reduce both SO_2 and mercury. The technology for NO_x reduction (selective catalytic reduction, or SCR) has also been found to oxidize elemental mercury that can be effectively captured in a downstream wet scrubber. The conversion (fuel switching) of coal-fired boilers to burn natural gas (in a simple cycle gas-fired boiler or combined cycle gas turbine) offers great potential to reduce emissions of SO_2 and mercury (almost 100 percent) and NO_x (70 to 80 percent). Baghouses (FFs) and electrostatic precipitators (ESPs) control fine particles and some mercury, while the combination of the two substantially reduces mercury emissions. These are examples where multi-pollution controls may reduce mercury emissions, while specific mercury controls may not be economically feasible (NEG/ECP, 2000).

658. The US government, academics and industry are collaborating, with some Canadian support, on programmes to determine the extent of affordable mercury reduction from coal fired generating stations.

Conclusions regarding secondary emissions control

659. It must be remembered that the characteristics of the raw material, the combustion process (or other high temperature process), and the specifications of the control equipment all influence the eventual emissions of mercury from the exhaust generated by a given plant. For example, mercury captured with the fly ash from a bituminous coal-fired boiler equipped with an ESP or FF may range from 36 to 90 percent as seen in table 8.5. Similarly equipped plants burning sub-bituminous coal or lignite may exhibit fly ash related mercury removal ranging from 0 to 30 percent of the mercury with the fly ash. If the plant is also equipped with a wet FGD scrubber (and depending on the type of coal burned and the scrubber design), nearly all of the remaining Hg^{2+} can also be captured. Mercury removal levels as low as 10 percent and as high as 95 percent have been measured in the USA for coal-fired utility boilers equipped with wet limestone (FGD) scrubbers (US EPA, 2002). If coal cleaning is carried out prior to combustion, data from the US Department of Energy indicate that typically 10 to 50 percent of the mercury in coal can be removed only in the cleaning process (US EPA, 1998). Figure 8.3 provides a simple summary of the most common control technologies, while table 8.6 briefly reviews other common applications.

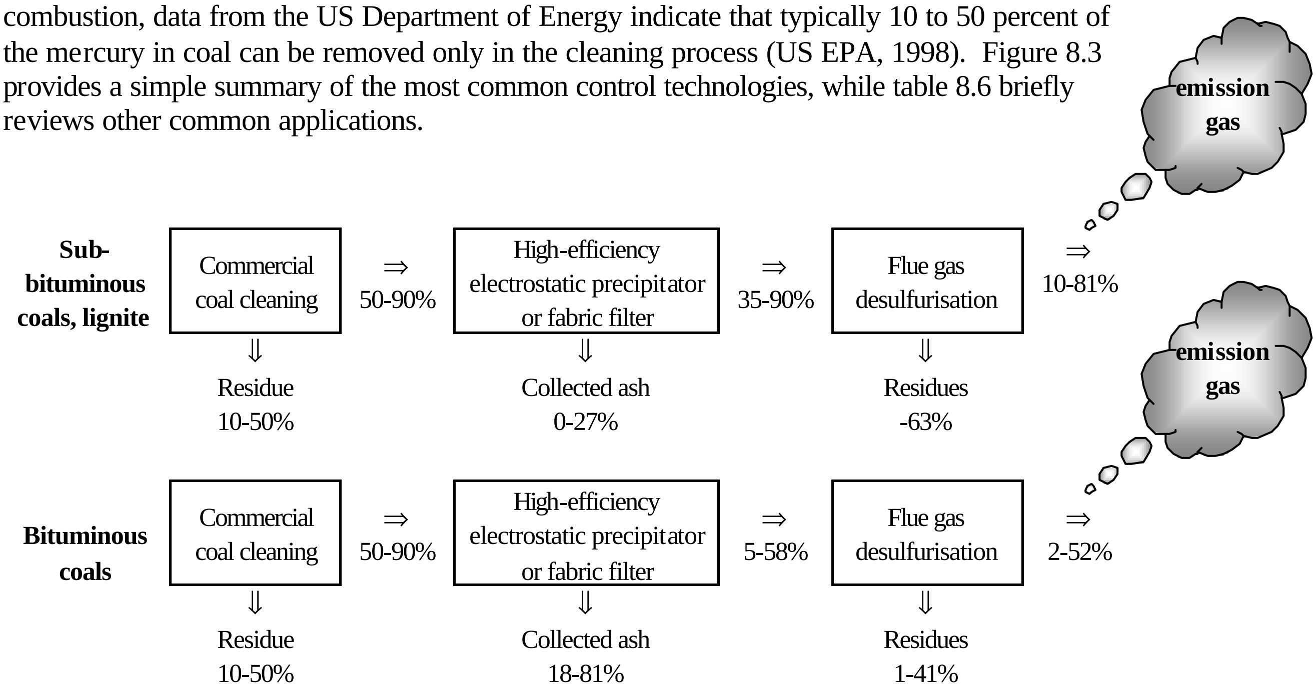

Figure 8.3 Reducing mercury emissions from utility boilers – typical efficiencies of key technologies

660. The mercury removal efficiencies in figure 8.3 may be compared with impressive results reported from a coal combustion unit in northeastern China, shown in figure 8.4.

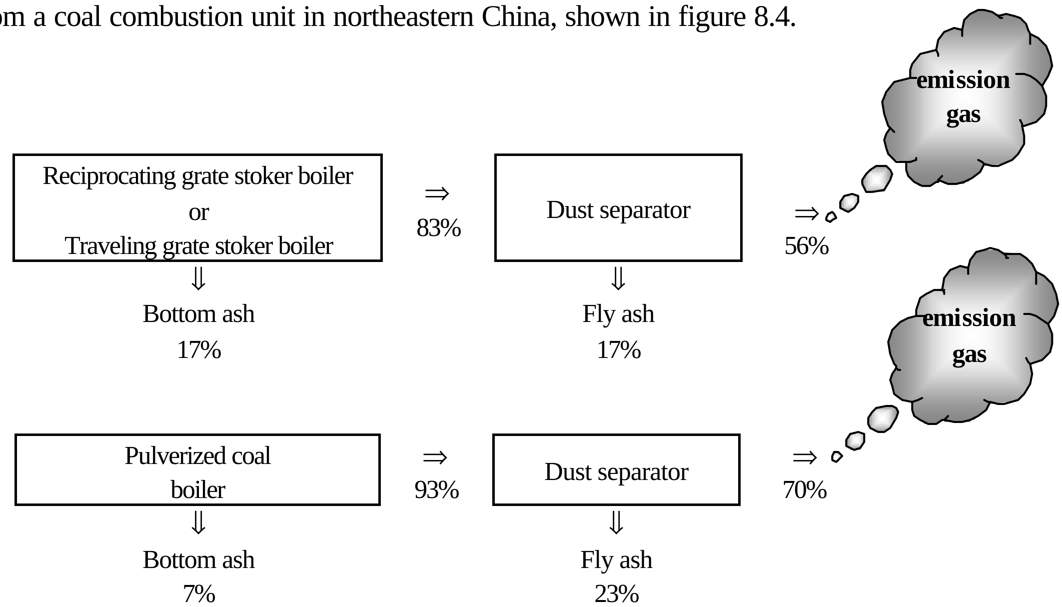

Figure 8.4 Reducing mercury emissions from coal combustion in China (Wang et al., 2000)

Table 8.6 Efficiency of common mercury control technologies for utility boilers (based on Pirrone et al.*, 2001)*

Emission source and choice of control technologies for utility boilers	Control combinations, effectiveness, final concentration of mercury in effluent, etc.
Coal-fired utility boiler emission controls a) wet flue gas desulfurisation (FGD) system b) spray dry FGD system c) downstream fabric filter ("baghouse") d) SO_2 absorption e) high-efficiency electrostatic precipitator (ESP) f) FGD wet lime/limestone-gypsum process with pre-scrubber	(a) achieves 30-50% reduction; potentially much better performance on bituminous coal-fired boilers. (b) achieves 35-85% reduction, in the higher range when supplemented by (c) (e)+(f) achieve 77% reduction (Netherlands) (e)+(b) achieve 75% reduction, of which 50-70% due to (e) (Bergstrom, 1983)
Coal fired utility boiler types and characteristics a) wet bottom boiler b) full burner load c) 50% burner load d) low burner load e) fluidized bed combustion f) pulverised coal-fired dry bottom boiler	(a) produces higher mercury emissions than alternative boilers (b) produces similar mercury emissions as (d) (c) produces half the mercury emissions of (b) and (d) (e) produces similar or lower mercury emissions than standard boilers (f) mercury emissions depend on coal type and control technologies used
Oil-fired utility boilers a) tangential unit b) horizontal unit	(a) and (b) have comparable mercury emissions

Abbreviations: ESP - Electrostatic precipitator FGD - Flue gas desulfurization

D. Control of incinerator emissions

661. Various countries rely to a greater or lesser extent on controlled waste **incineration**, which reduces the waste volume and (optimally) makes use of the energy contained in the waste materials. Because of its low boiling point, most of the mercury content of the waste evaporates during combustion, and is emitted directly to the atmosphere, unless the exhaust gas is properly controlled. In many countries emission controls on waste incinerators have been improved during the last decade, and this is reflected in decreased emissions of mercury (AMAP, 2000). In units fitted with control technologies, Pirrone *et al.* (2001) found that 35-85 percent of the mercury is removed by flue gas controls.

662. According to compliance tests recently conducted at 115 of the 167 large municipal waste incinerators, MWIs, in the USA, the average and median mercury control efficiencies for large MWIs were 91.5 percent and 94 percent, respectively. The average control efficiency at each site was based on a 3-test average determined by measuring the total flue gas concentration of mercury both before and after the control system at each site (injection of powdered activated carbon upstream of either a spray dryer and fabric filter baghouse, or a spray dryer and electrostatic precipitator).

663. The mercury eliminated from exhaust gases is retained in incineration residues and, for some types of filtering technology, in solid residues from wastewater treatment (from the scrubbing process). These residues are generally sent to landfills or – depending upon their content of hazardous materials and other characteristics – used for special construction purposes (wallboard, roadbeds or similar). In some cases such solid residues are stored in special deposits for hazardous waste, which are additionally secured with a membrane or other cover that eliminates or reduces releases by evaporation and leaching (Pacyna and Pacyna, 2000).

664. Typical control efficiencies for a municipal waste incinerator are shown in figure 8.5 below, and a greater range of common control measures in table 8.7. Note that additional releases from deposited ashes and residues are not reflected in the figure.

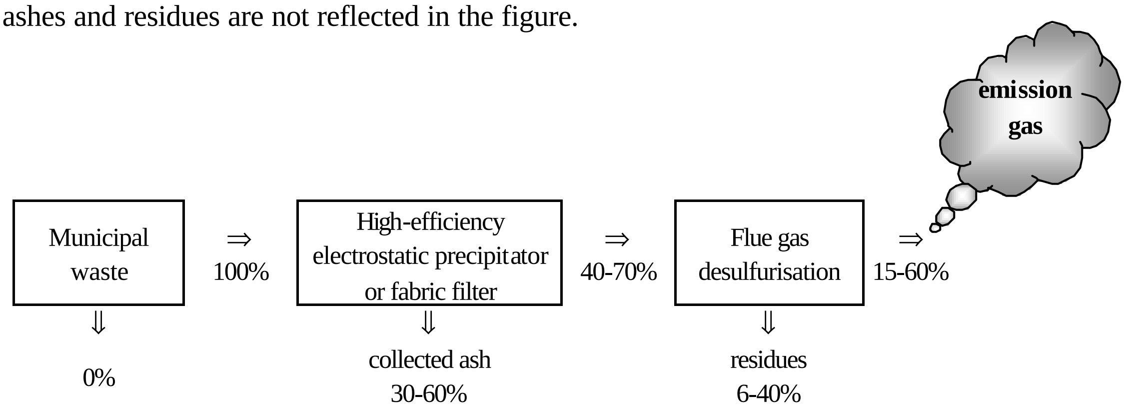

Figure 8.5 Reducing mercury emissions from waste incinerators – typical efficiencies of key technologies (based on Pirrone et al., 2001)

Table 8.7 Efficiency of common mercury control technologies for incinerators (based on Pirrone et al., 2001)

Emission source and control technologies for incinerators	Control combinations, percent reduction of mercury emissions, final concentration of mercury in effluent, etc.
Municipal waste incinerators (MWI) a) mass burn/waterwall (MB/WW) type of combustor b) high-efficiency electrostatic precipitator (ESP) c) spray dry FGD system d) downstream fabric filter ("baghouse")	(a) emits higher levels of mercury and compounds than other types of MWI (b)+(c) achieve 75% reduction, of which 50-70% by (b) (Bergstrom, 1983) (c) achieves typical 35-85% reduction, in the higher range when supplemented by (d)
Sewage sludge incinerators a) fluidized bed (FB) combustor b) multiple hearth (MH) technique	(a) emits lower levels of mercury to the atmosphere than other incinerators, and (b) emits more mercury than most

Abbreviations: ESP - Electrostatic precipitator; FGD - Flue gas desulfurization; FB - Fluidized bed; MH - Multiple hearth

Note: This table does not include the use of activated carbon injection as a control option. However, recent advances in the use of this technology are mentioned in previous paragraphs.

665. For comparison, figure 8.6 shows the behaviour of mercury in a specific Japanese incinerator (data provided by the Republic of South Korea). According to measurements, 98.2 percent of the mercury in the waste moves to the emission gas treatment facility, and only 2 percent remains in slag residues. Then, 14 percent of the mercury is removed by the electrostatic precipitator and remains in the collected ash and 91 percent of the mercury that passes the electrostatic precipitator (77 percent of total mercury) is removed by the gas cleaning facility. Finally, 7 percent of the mercury originally contained in the waste is emitted to the atmosphere.

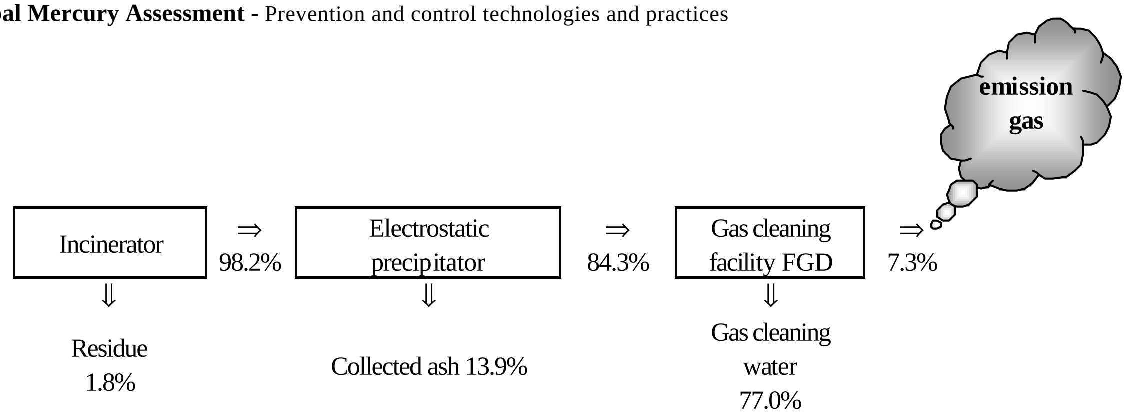

Figure 8.6 Behaviour of mercury in a Japanese incinerator (Nakamura, 1994).

8.3.4 Mercury removal from exhaust gases generated in industries other than utility boilers and incinerators

666. Processing of secondary raw materials such as iron and steel can also be a significant source of mercury emissions, and emission control technologies are often necessary. In this case the origin of the mercury may be from both natural impurities as well as from the intentional use of mercury in products/components (switches, air-bag activators etc.) that end up in iron/steel scrap.

667. Various techniques to remove mercury from exhaust gases generated by industries other than the production of electricity and heat, as well as during waste incineration have been developed, particularly for metallurgical processes. In one example, a selenium filter has been applied at both steel and non-ferrous plants. In this dry media process, mercury removal of 90 percent has been achieved, reducing the mercury concentrations to below 10 µg/m³. A carbon filter is also commonly used, with a mercury removal efficiency similar to that achieved with the selenium filter (Pacyna and Pacyna, 2000).

668. The lead sulfide process is another dry media technique used to remove mercury from flue gases generated in non-ferrous metal smelters. The gases containing volatile mercury are passed through a tower packed with lead-sulfide-coated balls. One study at a Japanese smelter in Naoshima indicates reduction of mercury concentrations from 1000–5000 µg/m³ in the feed to the absorption tower to 10-50 µg/m³ at the outlet (Pacyna and Pacyna, 2000).

669. The two major wet media processes to remove mercury from flue gases include the selenium scrubber and the so-called Odda chloride process. The selenium scrubber method is rather similar to the selenium filter technique. A mercury reduction of 90–95 percent can be achieved (Pacyna and Pacyna, 2000).

670. In the Odda chloride process, mercury vapours are oxidized to form mercuric chloride, which then precipitates. Mercury is recovered and mercuric chloride is regenerated. The mercury concentrations of the treated gases are 50-100 µg/m³ (Pacyna and Pacyna, 2000).

671. The effectiveness of these techniques is summarized in table 8.8, and other common technologies are reviewed in table 8.9.

Table 8.8 Efficiency of flue gas mercury removal techniques (Pirrone et al.*, 2001)*

Control technique	Typical Hg removal efficiency	Measured Hg content downstream (µg/m³)
Selenium filter	> 90%	< 10
Selenium scrubber	90-95%	200
Carbon filter	90-95%	10
Odda chloride process	n.a.	50-100
Lead sulfide process	90-99%	10-50

Table 8.9 Efficiency of mercury control technologies for other industries (based on Pirrone et al.*, 2001)*

Emission source and control technologies	Control combinations, percent reduction of mercury emissions, final concentration of mercury in effluent, etc.
Iron and steel industry a) electric arc (EA) process (normally used for special alloy steels and scrap) b) basic oxygen (BO) process c) open hearth (OH) process d) dry media selenium filter e) carbon filter process f) wet media selenium scrubber g) wet media Odda chloride process	(a) emits 10 times more trace elements than (b) or (c) (d) achieves up to 90% reduction of mercury emissions, to less than 10 µg/m³ (e) achieves up to 90% reduction of mercury emissions, to less than 10 µg/m³ (f) achieves 90-95% reduction of mercury emissions (g) may reduce mercury emissions to 50-100 µg/m³
Non-ferrous smelting processes a) dry medium selenium filter b) carbon filter process c) dry media lead sulfide process d) wet media selenium scrubber e) wet media Odda chloride process	(a) achieves up to 90% reduction of mercury emissions, to less than 10 µg/m³ (b) achieves up to 90% reduction of mercury emissions, to less than 10 µg/m³ (c) may reduce mercury concentrations from 1000-5000 µg/m³ before the absorption tower, to 10-50 µg/m³ of emissions at the outlet

8.3.5 Reducing releases of mercury from chlor-alkali facilities

672. In mercury cell chlor-alkali plants, mercury is used as a flowing cathode in electrolytic cells. Specific details of this process may be found in Lindley (1997), EIPPCB (2000) and various other references. Most releases of mercury from this process occur with the hydrogen gas, the end-box ventilation system and the electrolytic cell room ventilation air (US EPA, 1973).

673. Mercury releases from chlor-alkali operations can be entirely eliminated only by converting to a non-mercury process such as the membrane cell process. The fact that the membrane cell process is more energy efficient (Fauh, 1991) is one of several strategic and economic considerations that must be taken into account when a company decides to dismantle a mercury cell chlor-alkali facility and replace it with membrane technology.

674. When a mercury cell process is converted to a membrane cell process, certain parts of the process may remain the same. However, because residual mercury levels exceeding 10 parts per million (ppm) in the brine system can greatly affect membrane performance (O'Brien, 1983), a mercury removal system is required initially. The mercury removal process is needed until residual mercury is sufficiently purged from the brine (typically 1 or 2 years). The filters used for mercury removal can later be used for secondary brine treatment (Horvath, 1986). There are many other technological changes also required when making a conversion from mercury to membrane technology – although the complexity and cost of these are highly dependent on the circumstances of the individual plant. A typical example is the need for brine of far higher quality for the membrane process. Supply of such brine often requires the installation of a new brine purification plant, and may also require a change of raw material source.

675. As mentioned, there are electricity savings associated with plant conversion, as well as other operating cost savings such as the avoidance of costs of recycling or disposing of mercury wastes, although these costs are uncertain (US EPA, 1997). While the actual figures are highly plant dependent, the World Chlorine council has suggested that most estimates for total operating cost savings fall in the range of $US30 to $50 per metric ton of chlorine capacity. These savings, accrued over the plant's lifetime, may be compared with the initial investment cost of conversion, which may typically be on the order of $500 per metric ton of chlorine capacity.

676. Other than complete conversion to an alternative process, primary opportunities for reducing atmospheric mercury emissions from the mercury cell chlor-alkali production process require paying particular attention to the by-product hydrogen stream, end-box ventilation air, and cell-room ventilation air. Typical devices/techniques for removal of mercury from stack emissions are: 1) gas stream cooling to remove mercury from the hydrogen stream, 2) mist eliminators, 3) scrubbers, and 4) adsorption on activated charcoal and molecular sieves. The proper use of these devices can remove more than 90 percent of the mercury from the gas streams (Pacyna and Pacyna, 2000).

677. However, most mercury losses from chlor-alkali facilities are fugitive. Relevant preventive measures include:

- Equipment cool-down before opening for invasive maintenance;
- Consolidation of maintenance actions to minimize the number of invasive maintenance events;
- Draining mercury from a components before it is opened or keeping its internal mercury covered with cooling water or installing a hood to capture mercury vapour;
- Capital investment in larger-capacity decomposers that require less invasive maintenance;
- Improving the purity of brine so as to prevent build-up of mercury wastes that require invasive maintenance;
- Use of longer-lasting metallic anodes that necessitate less invasive maintenance;
- Capital investment in new elongated cells with air pollution prevention features like internal mechanical arms that can accomplish some maintenance actions that formerly required invasive maintenance.

678. Further comprehensive information on relevant abatement options can be found in EIPPCB (2000) in “Guidelines for Mercury Cell Chlor-alkali Plants Emission Control: Practices and Techniques,” at <http://www.cl2.com/AM2001/index.html>, and in a similar series of guidelines and documents available on the Euro Chlor site at <http://www.eurochlor.org/>.

679. As an example of recent progress in this area, the US mercury cell chlor-alkali companies have voluntarily reduced mercury consumption by 81 percent since 1995 to about 28 metric tons in 2001. Adjusted for a decline in production capacity during that period, the “real” decrease was 75 percent. According to industry reports, these reductions have been made through a variety of equipment upgrades and improvements to housekeeping practices that have limited the vaporization of mercury from the mercury cell room. Likewise, using similar technological improvements and changes in management practices, the industry in Western Europe has voluntarily reduced mercury emissions to the atmosphere[24] by 96 percent since 1977.

8.3.6 Reducing mercury releases from artisanal gold mining operations

680. According to CETEM/IMAAC/CYTED (2001), since 1980 small-scale gold mining activities have increased steadily. This report also estimates that small-scale mining may account for as much as one-quarter of the world gold output. Despite the current low gold price, the gold rush in the artisanal sector continues. Chapter 7 has documented the importance of mercury releases from these activities. UNIDO’s participation and objective in addressing this problem is to replace low-recovery, high-mercury-consuming and -discharging processes with environmentally safe and high-yield gold extraction alternatives that will sharply reduce or eliminate the use and discharge of mercury.

A. Diverse measures to reduce mercury releases and exposures

681. According to CETEM/IMAAC/CYTED (2001), since training and awareness-raising are important tools for getting results in the small-scale mining sector, UNIDO focuses on:

- On-the job training in cleaner technology;

[24] While mercury emissions to the atmosphere (European industry data) cannot be directly compared to mercury consumption (US industry data), the main point of this paragraph is that a large part of the industry has made a serious effort to improve its environmental performance.

- Training of women and women entrepreneurs, who have a big share in the sector;
- Enhancing awareness through workshops on local, regional and international level;
- Raising the interest of the media. Among others, BBC and CNN have already reported on the mercury-related activities of UNIDO.

682. In order to successfully introduce alternatives to present polluting practices, one needs to:

- Familiarize local manufacturers with the design of low-tech but efficient gold recovery equipment;
- Demonstrate alternatives to amalgamation;
- Prove the cost effectiveness of the new techniques;
- Develop micro-financing programmes in cooperation with the private sector.

683. The involvement and commitment of the local community is crucial, including the following elements:

- Clear community understanding of the problem;
- Commitment of community resources to deal with it;
- Meetings of all the stakeholders involved in the discussions to reach a consensus:
- After consensus is reached, a programme of action including: a) closed circuit utilization of mercury in the concentration/amalgamation steps; b) burning of the amalgam in retorts in the field, and use of fume hoods in gold dealers' shops; and c) confinement of processed material in specially built settling ponds;
- Agreement to adopt these measures both for the present operations and to avoid future problems;
- For the present operations, sampling the levels of mercury pollution, assessing risk areas, and carrying out isolating and remediating measures to ensure mercury fixation and/or recovery.

684. Other more obvious measures should also be implemented, such as:

- No spilling of mercury during the amalgamation phase, being a matter of mercury management throughout the process;
- Use of amalgamation vessels;
- Processing of the ore in a closed loop;
- Use of retorts in order to collect the mercury vapours;
- Use of fume hoods (preferably with carbon filters) at gold shops.

685. For a field manual on how to process alluvial gold ores and manipulate mercury safely, see CETEM (1994).

B. Amalgamation centers

686. UNIDO (1997) has noted that a very creative solution has been implemented in Venezuela - Amalgamation Centers. This solution can be easily reproduced in other countries. Miners take their gravity concentrates to these centers to be safely amalgamated by technical operators. In the Amalgamation Centers in Venezuela operated by the government, the service is free. In private centers, miners pay US$ 0.7 per kg of concentrate to be amalgamated.

687. Based on the Carhuachi Center, a remarkable Amalgamation Center at Caroni River, UNIDO and a Venezuelan non-governmental organization known as PARECA designed a center called UNECA (UNit for gold Extraction and Controlled Amalgamation). At the center, gold is processed by trained operators using special amalgamation plates or leaching using the NaCl electrolytic process. Both methods reduce the use of mercury. The electrolytic process actually eliminates amalgamation. Special retorts and melting furnaces working under fume hoods with charcoal filters impregnated with iodine are used.

688. The UNECA-type amalgamation center is suitable for installation in mining villages or in any central area to facilitate miners bringing gravity concentrates. Gold recovery is actually improved and mercury exposure to the operators is insignificant. For a miner who takes his concentrate to an amalgamation center, there is the added benefit of reducing costs in his own processing plant. These centers play an important role in diffusing information about mercurialism caused by mercury vapour and ingestion of contaminated fish. Miners can be given information while they wait for the processing of their concentrates. The centers can also provide advice for miners on how to improve their production, and can provide a meeting place for other purposes of education and organization.

C. Individual measures

689. Other measures may be focused directly at the individual artisanal miner to reduce his/her releases of mercury. Retorts can be used to capture volatilized mercury and condense it, resulting in substantial reductions in air emissions and occupational exposures, and allowing the mercury to be recycled a couple of times before its capacity to recover gold has been too much reduced. Some retorts are made of stainless steel while others are homemade of inexpensive iron pipes and connections. Mercury losses during retorting depend on the type of connections or clamps used, and the mercury recovery is typically 51-99 percent (Farid *et al.*, 1991). Retorts are not widely used in the goldfields because of uncertainty among the miners about what may happen to the gold when they do not have continuous eye contact with the amalgam during the retorting process. There is some fear that the temperature might be so high that the gold also evaporates, or that the gold may somehow be stolen. Moreover, after so many hours of hard work it is thrilling to watch every step of the transformation of the amalgam to gold. Finally, those who profit from selling mercury have been reported actively discouraging any such innovation that may reduce their market.

690. Other methods for abating mercury emissions when an amalgam is heated are also available and can be easily implemented. According to UNIDO (1997), already in 1989 a Brazilian company had developed a mercury condensing fume-hood. The prototype had a series of condensing plates coupled with activated charcoal filters impregnated with an iodine solution. More than 99.9 percent of mercury from the fumes were reported to be retained by this special fume-hood. Less than 40 $\mu g/m^3$ of mercury was detected in the interior of the shop during a gold smelting operation, compared with other measurements as high as 300 $\mu g/m^3$ in unprotected shops[25]. A similar technique was used by the Amalgamation Center of Carhuachi in Venezuela. This simple solution should be applied to all gold dealers in Latin America, which will result in a significant reduction of mercury emissions in urban areas.

8.4 Waste management practices

8.4.1 Mercury wastes and inventories

691. As described in chapter 6, mercury in waste can be a significant source of mercury releases, especially as waste management practices vary considerably around the world. Recalling from chapter 6, the diversity of waste streams that need to be carefully monitored are summarized in table 8.10. In addition, there are some very large inventories of mercury that could give rise to significant releases if not managed responsibly, see table 8.11.

692. In one example, the US Department of Defense "strategic" stockpile of virgin mercury was decided to be sold in the early 1990's. US EPA subsequently convinced the defence department to delay further sales until some sort of control system could be worked out to prevent eventual uses that could not be adequately controlled. The delay remains in place, but no long-term solution has yet been found.

693. In a second example, chlor-alkali mercury poses a special challenge (see also section 7.4). As plants are decommissioned in Western Europe, "used" mercury is becoming available in large quantities - about 500 metric tons per year in 2000 and 2001, according to Euro Chlor. This mercury is virtu-

[25] For comparison, background atmospheric mercury in cities is about 0.01 g Hg/m^3, the limit for public exposure is 1 g Hg/m^3 and the limit for industrial exposure is 50 g Hg/m^3 (UNIDO, 1997).

ally "pure" and therefore reusable (for most applications) without reprocessing. The European Commission was asked by the Environment Council (meeting 7 June 2001) whether some sort of coordinated action is necessary within the EU member states in order to control the eventual fate of this mercury. The industry has agreed for the present to put it under the control of the Spanish mining company Miñas de Almadén on condition that it replaces, ton-for-ton, mercury that would otherwise have been newly mined and smelted to satisfy normal market demand.

Table 8.10 Waste streams giving rise to mercury releases

Waste emissions of mercury to the atmosphere
▪ Incinerator waste water treatment plant sludge ▪ Diffuse releases from uncollected waste products (fluorescent lamps, batteries, thermometers, mercury switches, electrical and electronic components, lost teeth with amalgam fillings etc.) ▪ Evaporation of mercury disposed of in landfills ▪ Mercury wastes that go to municipal, medical or hazardous waste incinerators ▪ Mercury contained in scrap metal used in secondary metal production ▪ Mercury emissions from other treatment processes, including retorting facilities and stabilisation
Waste discharges of mercury to water – aquatic environment
▪ Direct discharges from industry and households to water drains ▪ Indirect discharges via waste water treatment systems ▪ Informal disposal in the water, and surface run-off from informal disposal on land ▪ Leachate from landfills without leachate collecting membranes and leachate effluent cleaning systems
Waste releases of mercury to the soil – terrestrial environment
▪ Disposal on land (informal) or in landfills – with or without protection of groundwater and surrounding soil (membranes and leachate water cleaning system) ▪ Diffuse releases from uncollected waste products (batteries, thermometers, mercury switches, electrical and electronic components, lost teeth with amalgam fillings etc.) ▪ Local releases from industry: On site materials and waste storage, broken/unused pipes, equipment and building materials ▪ Spreading of sewage sludge with trace contaminants on agricultural land (used as fertiliser) ▪ Use of solid residues from waste incineration and coal combustion for construction purposes (slag/bottom ash and fly ash)

Table 8.11 Key inventories of mercury that must be responsibly managed

Waste quantities or inventories of mercury that need to be managed
▪ So-called "strategic" mercury stockpiles held by a number of governments ▪ Large quantities of mercury recovered from mercury-cell chor-alkali facilities at the time of decommissioning or changing to a non-mercury process

8.4.2 Prevention and control measures

694. Since all of these sources of (potential) mercury releases have been previously described, this section will focus primarily on the sorts of measures that may be applied for preventing (long-term solutions) and controlling (usually short- to medium-term solutions) those releases. Many problems might be simplified, of course, if mercury substitutes were more widely used and the mercury content of various waste streams were much reduced. However, this chapter assumes that the mercury is already in the waste, and then suggests how best to deal with it. As in the case of industrial releases, one may consider a range of non-technical and technical measures that might be applied.

A. Non-technical measures

695. Non-technical measures for preventing and controlling releases from waste streams may typically be divided among regulatory/prescriptive measures, economic measures, and educational/information measures. Some examples follow.

(1) Regulatory/prescriptive measures

- Prohibit mercury in product waste and in process waste from being released directly to the environment, by means of an effective waste collection service;
- Prohibit mercury in product waste and in process waste from being mixed with less hazardous waste in the general waste stream, by ensuring separate collection and treatment;
- Set limit values for the allowable mercury content in sewage sludge spread on agricultural land;
- Restrict the use of solid incineration residues in road-building or other applications where its long-term control cannot be assured;
- Prohibit the re-marketing of used, recycled mercury;
- Prohibit illegal dumping of wastes;
- Prohibit any direct or indirect discharges of mercury to normal drains or the water treatment system, or any disposal of mercury in water;
- Prohibit or restrict cross-border transport of mercury (and other hazardous) wastes;
- Require that any mercury containing waste or materials stored on-site by an industry or commercial operation must be in air-tight and waterproof containers, and that the organization must have a written plan and schedule for eventual proper disposal of the materials;
- Prohibit the disposal on land of any sewage sludge, fertilizer, or other material that exceeds responsible international standards for mercury content;
- Put in place an environmental management strategy that includes responsible monitoring and enforcement of mercury regulations, tracking of all mercury movements (from raw material to process to product to waste), and periodic independent control.

(2) Economic measures

- Set taxes and fees on hazardous waste disposal (special incineration, dedicated landfill, etc.) that fully reflect the real long-term costs to society and the environment of responsibly dealing with these hazardous substances.

(3) Information and educational measures

- Educate the public about proper disposal of mercury containing products;
- Provide collection points where the public may easily take these separated products;
- Devise several key indicators and publicize the progress that is being made with regard to responsible management of mercury.

B. Technical measures

696. Technical measures for dealing with mercury wastes may be divided between pre-treatment measures and emission control measures.

(1) Pre-treatment measures

- Prohibit or limit mercury releases to the environment by treating household waste, hazardous waste and medical waste by emission control technology.

(2) Emission control measures

- Require landfills to be properly licensed and equipped for the type of hazardous waste they accept, including membranes to prevent mercury from evaporating or leaching, collection and

treatment of landfill effluent, routine and long-term testing of groundwater quality, air emissions, etc.;
- Ensure that mercury wastes are incinerated only at facilities equipped for hazardous waste, with best-available-technology dust collectors and flue gas control, etc.;
- Develop a facility (perhaps jointly with a neighboring country) for final disposal of mercury (and other) treated wastes that are so concentrated or hazardous over the long term that they cannot be responsibly disposed of in another manner.

C. Limited long-term solutions

697. As explained in chapter 6, most of the options above are short- to medium-term measures. One of the only real long-term measures is prevention (keeping mercury out of the waste stream). Once present in the waste stream (if pollution control is considered a priority), mercury contributes to the need for emission controls on incinerators, special disposal of incinerator residues, landfill leachate treatment etc. – all associated with extra costs. Even those countries that make an effort to separate mercury products from the general waste stream have found it difficult to achieve satisfactory collection rates, and they have discovered that separate collection and treatment implies significant extra costs for society. Therefore, with regard to mercury in products, minimising the intentional use of mercury may be a highly desirable objective. This has been the main driving force behind the mercury substitution policy of many countries.

698. Another long-term measure for mercury waste management is intermediate storage/definitive storage in a special facility, such as that described below.

8.4.3 Responsible management of mercury inventories

A. Take-up by Almadén

699. As described in chapter 7, one of the solutions proposed for mercury from decommissioned chlor-alkali facilities is shipping it to the Almadén mercury mine in Spain, which has agreed to decrease its mining production and to market the chlor-alkali mercury instead. Some feel that there are not yet adequate controls on where this mercury would then be sold by Almadén, or how it would be used.

B. Intermediate storage

700. Another proposal is that the mercury could be stored safely for an indefinite period of time until a strategy for closed-loop re-use or safe disposal is available. This option has the advantage that the mercury would be available if some important new need is identified. It could lead to some releases, ongoing management costs, and is still not a final solution. However, ongoing management costs and the risk of significant releases outside the intermediate storage enclosure would be small if best management practices were implemented.

C. Terminal/permanent storage

701. It has been argued that, from an environmental point of view, terminal/permanent disposal of mercury would be preferable. However, this could encourage continued mining and smelting of virgin mercury to meet ongoing demand. Further, it has been argued, the deposited mercury could be difficult if not impossible to recover if important new (and "closed-loop") uses were to emerge in the future.

702. Sweden has developed a strategy for terminal storage of surplus mercury and mercury containing waste. The strategy was developed as a response to concerns about what to do with the mercury collected from consumer products, industry and high-level mercury waste, which is currently in intermediate/provisional storage. Although the legal framework needs to be developed, and there are various technical issues related to waste treatment that need to be worked out, as well as the location and design of the terminal storage facility, a viable concept has been developed and proposed. The concept includes a suggestion that the waste owners bear full responsibility for constructing, managing and operating the facility. Excluding pre-treatment, estimates of the eventual cost of this option are on the order of $US 14-20 per kg of mercury. To put this figure in some perspective, this terminal storage cost

would add 6-10 percent to the estimated cost of converting a chlor-alkali facility from the mercury process to the membrane process.

703. The terminal storage concept is based on the conversion of mercury, currently stored in the elemental form or as high-level mercury containing waste, to a chemically stable form (e.g. mercuric sulphide, HgS), and subsequent disposal of the stabilised mercury in deep-rock storage. A number of investigations of waste treatment technology, chemical stabilisation, geochemistry, geohydrology and economics have been carried out, and the results of these investigations indicate that the concept is technically and economically feasible.[26] Although a range of issues remain to be addressed, the terminal storage strategy is scheduled for implementation in the near future in Sweden.

704. While other options for waste treatment and facility design will also be considered, at present the main components of the proposed terminal storage concept are:

- Conversion of mercury from high-level waste, batteries, electrical devices, etc., to the elemental form via thermal treatment and condensation of liquid elemental mercury;
- Conversion of the elemental mercury to the sulphide form via thermal treatment with, e.g., sodium sulphide or other suitable reagents;
- Storage of the mercury sulphide in a deep-rock storage facility equipped with appropriate monitoring devices.

705. Physical requirements for the terminal storage facility include geological stability, low water permeability, and absence of mineral resources which are or may become economically feasible to excavate. The terminal storage may be located in an abandoned mine shaft with well known geological and geohydrological characteristics.

706. It is important to note that the concept of deep-rock terminal storage was not developed as a method to reduce current mercury releases to the environment or current exposures. Rather, it was designed as a long-term solution to the problem of storing mercury wastes - in light of the persistence of mercury and the need for long-term strategies to reduce mercury pollution.

8.5 Mercury control costs and effectiveness

707. While the costs of control technologies are highly variable, depending on the country and location, local circumstances, availability of equipment and technicians, characteristics of raw material being combusted or waste being incinerated etc., this section draws on several key sources to provide some comparative estimates of these costs.

8.5.1 Costs of reducing mercury emissions from boilers and incinerators

A. Mercury control costs for utility boilers

708. As mentioned on page 14 of NEG/ECP (2000), "[US EPA] estimates of the cost effectiveness of various mercury emission reduction approaches vary widely," from $US 11-66 per gram of mercury removed using carbon injection,[27] to $US 143-933 per gram of mercury removed for fuel switching. These figures may appear high compared to general costs for reducing conventional pollutants such as

[26] In early 2002, US EPA completed its own research on mercury treatment by stabilisation and amalgamation. Two samples were used in this research – elemental mercury and a mercury waste containing 5000 ppm of a variety of mercury species. Based on the results of these studies, US EPA does not believe that treatment alone is sufficient for the long-term management of mercury wastes containing high levels of mercury, and for excess mercury inventories. US EPA is not convinced the wastes will remain in a stable condition when exposed to the full range of landfill conditions that exist in the USA.

[27] US EPA estimated this range of costs for carbon injection on a coal-fired, 975 MW boiler at a 90 percent mercury removal rate. Note that while NO_x control costs are applicable to full-scale applications, mercury control costs are based on pilot-scale data and, therefore, are more developmental in nature. Data from ongoing full-scale demonstrations are expected to refine mercury control costs.

nitrogen oxides (NO_x), sulfur dioxide (SO_2) and particulate matter (PM). While any such comparison must be carefully interpreted due to the entirely different nature of the emissions, quantities, effects, etc., US EPA has presented a comparison as summarized in the box below.

Comparison of Mercury and NO_x Control Costs (US EPA, 2002)

An understanding of mercury control costs may be gained by comparing them with costs of currently used controls for NO_x. In the USA, commercial NO_x control technologies are being used to comply with emission reduction requirements. Therefore, the costs associated with these NO_x controls are being experienced at full-scale applications. A comparison of mercury control costs with costs of currently used NO_x controls provides insight into how far or near the mercury control costs are from costs that are presently being experienced at full-scale applications to control another pollutant.

Table 8-10 below presents the ranges of total annual costs in 2000 constant dollars for the mercury controls examined in this work and for two currently used NO_x control technologies; i.e., low NO_x burner (LNB) and selective catalytic reduction (SCR). The NO_x control costs presented are for applications on dry-bottom, wall-fired pulverized-coal boilers ranging in size from 100 to 1000 MW and being operated at a capacity factor of 0.65. In general, costs associated with LNB and SCR are expected to span the costs of currently used NO_x controls; therefore, these costs were chosen for comparison with mercury control costs.

As seen from Table 8-10 below, total annual costs for mercury controls lie mostly between applicable costs for LNB and SCR. However, Table 8-9 (*not shown here*) shows total annual costs of mercury controls to be higher for the minority of plants using HS-ESPs (hot-side electrostatic precipitators). Excluding these costs, both currently estimated and projected mercury control costs are in the spectrum of LNB and SCR costs.

Table 8-10

Air pollutant controlled	Control technology	Total annual control cost range ($US/MWh generated)
Hg	Powdered activated carbon injection	0.305 to 3.783 (a) 0.183 to 2.270 (b)
NO_x	Low- NO_x burners	0.210 to 0.827 (c)
	Selective catalytic reduction	1.846 to 3.619 (c)

(a) current estimate of costs (b) projected costs (c) actual costs

709. It is important to recognize that the ultimate cost of controlling mercury from utility boilers will be dependent upon the potential impact that mercury control has on the sale and/or disposal of the combustion by-products. For example, for plants that sell their fly ash for cement manufacturing, the use of activated carbon injection could dramatically reduce their ability to sell this material due to increased carbon concentrations. For plants that elect to use a wet scrubber to capture mercury, their ability to sell their gypsum for use in wallboard manufacturing could be compromised by increased concentrations of mercury. The potential impacts of additional mercury control on the use of by-products or the disposal of residues have not yet been determined. Such considerations may significantly affect an operator's costs of controlling mercury emissions from coal-fired boilers.

710. It must also be mentioned that mercury presents a far greater health and environmental hazard on an equivalent weight basis than do SO_2, NO_x, and PM. The costs are more similar to those associated with the control of dioxins and furans, which are produced in flue gases in extremely small quantities, and where any emissions at all are a concern. As is the case with effective controls of these compounds (scrubbers and baghouses are very effective at capturing dioxins and furans), it is important to note that many mercury control strategies also reduce other pollutant emissions, and vice versa. Fuel

switching, for example, can dramatically reduce emissions of NO_x, SO_2, carbon dioxide (CO_2), and particulates, while scrubbers remove many other toxics in addition to mercury. When the costs of these strategies are allocated among all the pollutants reduced, their cost-effectiveness is much improved.

711. Summary information on relative control technology costs is provided in table 8.12. This table indicates an apparent cost-effectiveness advantage for activated carbon injection, with the caveat that additional equipment is needed to remove other pollutants. However, it also demonstrates the popularity of the combination of electrostatic precipitator (ESP) or fabric filter (FF) and wet flue gas desulfurization (FGD), for which the initial investment (for a plant approaching 1000 MW capacity) is about $US 25 million greater, but operation & maintenance costs are nearly $US 6 million/yr less than for activated carbon injection.

Table 8.12 Rough cost-effectiveness of mercury control measures for utility boilers (based on Pirrone et al.*, 2001). Please refer to the source for further details.*

Control options for utility boilers	**Mercury removal efficiency (percent)**	**Costs**	
		Investment ($US 1000/MW)	**Operation & maintenance ($US 1000/MW/year)**
ESP only	10**	1.6	0.2
FF only	29**	28.9	5.8
ESP or FF + wet FGD	85	59.0	2.5
SDA + ESP	67	143.	5.0
ESP + carbon filter bed * [Based on the costs noted, this is not a practical option]	90-95	264.0	62.0
Activated carbon injection + FF *	50-90+	34.6	8.1

* Mercury control technologies.

** On the basis of previous discussions, this number appears low.

Abbreviations: ESP - Electrostatic precipitator; SDA - Spray dryer absorber; FF - Fabric filter; MW - Megawatt; FGD - Flue gas desulfurization; MWh - Megawatt-hour

B. Mercury control costs for incinerators

712. Incinerators employ many of the same mercury control technologies used in utility boilers. However, the cost structure is much different, so it is useful to present them in a separate table, and to compare incinerator control costs with other incinerator control costs rather than with utility boiler control costs. Once again, it should be kept in mind that the costs calculated in table 8.13 assume that the entire cost of emission controls is allocated to mercury alone, which is clearly not representative of the real world situation. Each of the control options discussed in the table has some effect on greenhouse gases and other emissions, and these effects must be taken into consideration before final decisions on multi-pollutant control technologies are made.

713. In conclusion, the relative costs and mercury removal effectiveness of the most common control technologies applied to incinerators are presented in table 8.14. In this case activated carbon injection seems to clearly lead the field in cost effectiveness, although its ability to remove other pollutants from the flue gas is greatly limited. It is therefore combined with an electrostatic precipitator or a fabric filter.

Table 8.13 Control technologies and cost effectiveness for incinerators (US EPA, 1997)

Source	Mercury control technique	Cost effectiveness		Cost comments
		$US/g Hg removed	Other indicators	
Municipal waste combustor (MWC)	Material separation (batteries)	$3.19	$0.41/metric tons MSW	Costs very community specific; results shown based on one community's program.
	Product substitution (e. g., batteries, thermometers etc.)	[see comment]	[see comment]	The potential for product substitutions requires that the specific circumstances of each situation be examined; general cost estimates are not possible.
	Activated carbon injection	$0.46 – 1.92	$0.77-3.85 metric tons MSW	Costs assume an 85% reduction; the range of costs covers two model plants. Costs equivalent to 1.3% (large unit) to 6.9% (small unit) calculated cost increase*
	Carbon filter beds	$1.13 – 2.39	$5.98-10.33/metric tons MSW	Range of costs covers two model plants.
	Polishing wet scrubber	$3.52 – 7.31	$5.83-14.85/metric tons MSW	Costs assume an 85 percent reduction; range of costs covers two model plants.
Medical waste incinerator (MWI)	Material separation (batteries)	less than $3.19 [see comment]	less than $0.41/metric tons MSW [see comment]	Costs vary on a site-specific basis; no costs were available; cost effectiveness for a hospital program would be assumed to be better than for a community program.
	Good combustion, wet scrubber or dry scrubber with carbon injection	--	--	For cost- effectiveness estimates for individual facilities, the reader should consult *Hospital/ Medical/ Infectious Waste Incinerators: Background Information for Promulgated Standards and Guidelines - Regulatory Impact Analysis for New and Existing Facilities* (EPA- 453/ R-97-009b)
	Switching with waste segregation		0.01-0.04% calculated cost increase*	
	Switching without waste segregation		0.02-0.09% calculated cost increase*	

* "Calculated cost increase" is the estimated cost increase in the service or product to cover the cost of these emission controls.
Abbreviation: MSW - municipal solid waste

Table 8.14 Cost-effectiveness of mercury control measures in waste incinerators (based on Pirrone et al., 2001) (ton = metric ton)

Control option	Mercury Removal efficiency	Costs			
		Investment		Operation & maintenance	
Municipal waste combustor	**(percent)**	**($US 1000/ton waste)**		**($US 1000/ton waste/yr)**	
capacity of MWC		**~180 t/day**	**~2000 t/day**	**~180 t/day**	**~2000 t/day**
ESP only	10	n.a.	n.a.	n.a.	n.a.
FF only	29	n.a.	n.a.	n.a.	n.a.
ESP or FF + carbon filter bed	99	31.7	80.0	6.5	15.6
Activated carbon injection + ESP or FF	50-90+	0.3	0.8	0.25	1.3
Polishing wet scrubber + ESP or FF	85	10.3	22.9	1.9	4.9
Medical waste incinerator	**(percent)**	**($US 1000/ton waste)**		**($US 1000/ton waste/yr)**	
capacity of MWI		**~60 kg/hr**	**~460 kg/hr**	**~60 kg/hr**	**~460 kg/hr**
ESP only	10	n.a.	n.a.	n.a.	n.a.
FF only	29	n.a.	n.a.	n.a.	n.a.
Activated carbon injection + FF	50-90+	56.5	127.0	89.0	84.0
Polishing wet scrubber + FF	85	400.0	400.0	100.0	100.0

Abbreviations:
ESP - Electrostatic precipitator
FF - Fabric filter (baghouse)
FGD - Flue gas desulfurization
SDA - Spray dryer absorber
MWh - Megawatt-hours
MWC - Municipal waste combustor
MWI - Medical waste incinerator

8.5.2 Costs of chlor-alkali conversion

714. Pirrone *et al.* (2001) and others (Lindley 1997, Fauh 1991, etc.) have noted that the membrane chlor-alkali process is more energy efficient than the mercury cell process. They have also pointed out that conversion from the mercury cell to the membrane process is possible utilizing some of the existing equipment. While keeping in mind the previous remark that the decision to convert from mercury cells to another process is not a purely economic decision, one may look more closely at the costs involved.

715. Euro Chlor, the association representing the European chlor-alkali industry, has estimated that conversion of a typical plant from mercury electrolysis to membrane electrolysis would cost about $US 500 per metric ton of chlorine capacity. US EPA (1997) produced estimates for conversion that are roughly in line with those of Euro Chlor. Lindley (1997) also estimated conversion costs for a typical West European chlor-alkali plant at the euro equivalent of about $US 500 per metric ton of chlorine capacity. Harris (2001) has estimated conversion costs in the range of $US 400-700 per metric ton of chlorine capacity, and operating cost savings in the range of $30-50 per metric ton of chlorine capacity, noting that the economic attractiveness of any given project will be highly dependent on its special circumstances, but concluding that conversion will be economically attractive only in exceptional cases.

716. It is informative to compare these high conversion costs with the striking reductions in mercury emissions (96 percent since 1977) in European, and in mercury consumption (75 percent since 1995) in the US chlor-alkali industries in recent years (see chapter 7) through a variety of equipment upgrades and improvements in housekeeping practices – at costs at least 100 times lower per gram of mercury prevented from entering the environment. In this perspective, the highest near-term priority, and the greatest reduction in mercury releases for a very modest investment, might be to extend this experience and these techniques as rapidly as possible to all other mercury-cell chlor-alkali plants around the world. Despite the reductions achieved by such measures, significant consumption of mercury must still be anticipated until conversion to mercury free technology takes place. The (US) Chlorine Institute's and (European) Euro Chlor's detailed guidelines on preventing air emissions and other releases should serve to indicate the most rapid and least expensive way forward.

8.5.3 Costs of dealing with releases from artisanal gold mining

717. Previously a long list of measures was presented for reducing releases and exposures from artisanal gold mining practices. Depending on the measures one wishes to pursue, the range of related costs is vast. Therefore the establishment of a typical amalgamation center was selected as an example of "extreme" measures that may have to be taken in order to really have a profound effect on a large number of miners in a given region.

718. According to UNIDO (1997) the cost of establishing a UNECA-type center (see section 8.3.6) depends on the process to be adopted (amalgamation with special plates and/or NaCl electrolytic leaching process), infrastructure needs, power supply, civil works, material costs, transportation and labor costs of the mining region. The estimated typical investment and operating costs are summarized in table 8.15.

Non-mercury processes for recovering gold

An **electrolytic process** to leach gold has also been developed by CETEM (UNIDO, 1997) - Center of Mineral Technology, Rio de Janeiro and tested in a pilot plant in the Tapajós region, Brazil. This process has the potential to replace amalgamation of gravity concentrates. Material with 1 ppm Au was mixed with sodium chloride (1 Mol/l), which is transformed by electrolysis into a mixture of sodium hypochorite-chlorate. More than 95 percent of the gold dissolves within 4 hours and is collected on a graphite cathode. The solution is always recycled minimizing effluent discharge. The NaCl and energy consumptions are 100 kg/metric ton of ore and 170 kwh/kg of Au respectively. Plastic leaching tanks are used, reducing investment cost. So the process is relatively uncomplicated and inexpensive with the potential for use. The main drawback of course, is the need for trained personnel to control operating variables (pH, current density, etc).

The UNECA-type Processing Center is suitable for installation in mining villages or in any central area to facilitate transportation of gravity concentrates. Gold recovery is actually improved and mercury exposure to the operators is insignificant. For a miner who takes his concentrate to a Processing Center, there is the additional benefit of reducing costs in his own processing plant. These Centers play an important role in bringing information about mercurialism caused by mercury vapour and contaminated fish ingestion. Miners can be given brochures and additional instructions while they wait for the processing of their concentrates. The Centers can provide advice for miners on how to improve their production and can provide a meeting place for other purposes of education and organization.

Another option has been reported from South Africa (MMSD, 2002), where the government's mineral technology research body, Mintek, has developed the new Minataur process. This involves treating the ore with hydrochloric acid in the presence of sodium hypochlorite and then using sodium metabisulphate or oxalic acid to precipitate the gold out as a concentrate that is 99.5% fine gold powder.

Table 8.15 Estimated capital cost of a UNECA Center (based on UNIDO, 1997)

Estimated fixed capital costs (equipment)	**US$**
Amalgamation-plates (2 sluices of eight 30x40 cm plates each in metallic frame)	20,000
Fume hoods, air filters, scrubbers, retorts, melting furnace	39,000
Electrolytic leaching system incl. filters and activated charcoal column	60,000
Other	10,000
Subtotal fixed capital costs	**129,000**
Estimated variable capital costs	
Civil construction + water works	20,000
Mechanical + electrical	10,000
Personnel costs (Engineer, laborers, expenses, training)	88,000
Subtotal variable capital costs	**118,000**
TOTAL CAPITAL COSTS	**247,000**

719. The costs presented in table 8.15 do not include power supply, which must be available on site, or the cost of land, which could be arranged by the local community. The total capital investment of nearly US$ 250,000 is high, but it can be greatly reduced after the installation of the first center as many local personnel can be trained, and as technology is transferred to local technical people who can be in charge of building other centers.

720. In addition to capital cost, one must consider operating cost, as presented in table 8.16.

Table 8.16 Estimated monthly operating costs for a UNECA Center (based on UNIDO, 1997)

Estimated operating costs	**US$/month**
• Labor & security personnel	4,900
• Electricity & gas	1,500
• Supplies & maintenance	6,000
• Mercury monitoring	500
• Proper disposal, etc.	2,000
TOTAL	**14,900**

721. As in Venezuela, the UNECA Center can charge US$ 1/kg of concentrate processed, thereby deriving an income of about US$ 10,000/month. This nearly covers the operating cost. The UNECA Centers are also decontamination centers. Using the electrolytic process, residual mercury and gold can be extracted from dredged "hot spots". Likewise, tailings produced by individual miners who continue to amalgamate their concentrates can also be treated in the Center. As the gold content in amalgamation tailings is high, as observed in Venezuela, the decontamination step might be profitably conducted by private companies. The Center should provide a safe landfill for the decontaminated residues.

8.5.4 Other costs and benefits

A. Human health benefits

722. The human health benefits associated with reductions of mercury in the biosphere have been addressed in detail in chapter 4.

B. Economic costs of mercury use, especially in products

723. The purely economic costs of dealing with the mercury in our products and our surroundings are considerable, but describing them in detail is not within the scope of this assessment. Nonetheless, several examples are worth mentioning, such as: cost of collecting separately mercury containing products; cost of recycling or acceptable disposal, whether to a special landfill or to a hazardous waste incinerator; cost of generating and enforcing legislation to deal with mercury in every sector of the economy; cost of tracking movements of mercury waste; cost of the extensive programmes in various countries (such as around the Great Lakes region of the USA and Canada) to significantly reduce mercury releases; cost of pursuing automobile companies to replace mercury switches; cost of special controls on municipal waste incinerators to remove mercury from the flue gases, etc. All of these examples represent costs to the local, regional and world economies that remain because mercury remains reasonably free to move through the economy.

C. Ecological and welfare benefits of reducing mercury pollution

724. As an example of a great variety of benefits that are often given little notice, it is instructive to consider in some detail the ecological and welfare benefits of reducing mercury pollution. As noted in US EPA (1997), mercury can adversely affect **ecological systems** at various levels: at the individual organism level, at the population level, and at the community or ecosystem level. While the effects on populations, communities, and ecosystems are of primary concern for most species, individual effects are also of interest because they may cause effects at higher levels of the ecological system, especially effects in vulnerable or reduced populations such as threatened and endangered species, raptors, and furbearers.

725. Likewise, there is a broad range of **cultural and welfare benefits** associated with reductions in the global mercury load. US EPA (1997) noted that the top three social and economic damages to native peoples were (1) diminishment of cultural and religious values; (2) damage to subsistence activities (e.g., subsistence fishing); and (3) damage to natural resources in commercial use. Fishing often plays a

role in all three of these areas. With respect to cultural values, for example, the Wisconsin Native Americans have built centuries-old traditions around spearing fish and sharing the catch. Growing concerns about limiting fish consumption and limiting the locations where fish may be caught seriously affect the Tribe's traditions (US EPA 1997).

726. The Arkansas Game and Fish Commission attempted to quantify fishing-related monetary losses due to mercury contamination as of 1994. Although the Commission has not published its findings (Armstrong 1994), it estimated a loss of fishing expenditures due to mercury fish consumption advisories of over $US 5 million from 1991 to 1992. This estimate was derived from decreased purchases of fishing license in counties where mercury advisories were issued, multiplied by the average number of trips an angler takes per year, and by the average per-trip expenditures. Changes in expenditures represent changes in welfare (US EPA 1997).

727. Other than the work cited above, little work has been done to quantify the value of most of these ecological and welfare benefits, which will vary greatly in any case from one region to another. Therefore, the summary provided in table 8.17 below is presented without any attempt at quantification.

Table 8.17 Summary of typical ecological/welfare benefits and the potential adverse effect on them from mercury pollution (from US EPA, 1997)

Ecological/welfare benefit or use category	**Adverse effect of mercury pollution**
Recreational Fishing	• Reduced number of fishing trips • Lost value per trip due to fish advisory • Lost value due to inability to consume fish
Commercial Fishing	• Lost value of fish exceeding maximum allowable concentration • Reduced demand for all fish due to perceived health threat
Subsistence fishing	• Lost value of fish no longer consumed • Lost nutritional value • Lost cultural value associated with subsistence fishing activity
Timber	• Reduced growth/productivity of commercial forests
Forest recreational activities	• Reduced number and/or value of recreational activities due to reduced quality of surrounding plants
Agricultural	• Reduced growth/productivity of crops
Recreational/Commercial Hunting/Trapping	• Reduced or lost commercial value of target species • Reduced value of recreational hunting/trapping activity with reduced population of target species
Recreational bird hunting	• Reduced number of trips for target species • Lost value per trip due to reduction in target species
Bird/animal viewing	• Reduced value of recreational activities with lower probability of viewing target species
Cultural/religious value	• Reduced cultural/religious value due to fish advisories, not associated with use
Existence value of specific species, including option value, bequest value, scarcity value, in addition to existence value	• Adverse effects on specific species (individuals and populations)
Biodiversity	• Adverse effects on biodiversity
Stewardship value, including moral obligation to reduce harm to ecological resources	• Adverse effects on specific species or in general
Preservation of ecosystem health, including maintaining the integrity of predator/prey relationships	• Adverse effects on ecosystem health