

CHAPTER-7. PRACTICAL OPPORTUNITIES AND TECHNOLOGIES AVAILABLE TO REDUCE ANTHROPOGENIC EMISSIONS OF MERCURY TO THE ENVIRONMENT

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7.1 INTRODUCTION

Various international and national organizations have been involved in developing strategies and policies to reduce emissions of mercury to the environment. The element has been given priority in this process compared to other trace metals. Major international activity on reduction of mercury emissions has been carried out within the UN Economic Commission for Europe (ECE) Convention on Long-range Transboundary Air Pollution Transmission (LRTAP). The UN ECE Working Group on Heavy Metals is now preparing protocols on emission reduction for these pollutants. Mercury is considered as priority element in addition to cadmium and lead.

In Europe, there are at least three other conventions working on the basis of international agreements which aim at the reduction of environmental fluxes of various pollutants, including mercury as a priority compound. These three conventions operate within the following programs: Oslo and Paris Commissions (OSPAR) program on reduction of land-based pollutants transported to the North Sea and the sister programs for the Baltic Sea (Helsinki Commission - HELCOM) and for the Mediterranean Sea (Barcelona Convention). There are also a number of national programs in the European countries aiming at the emission reductions of mercury.

In North America, various activities have been launched to reduce emissions of toxic pollutants including mercury. In the United States, Section 112(n)(1)(B) of the Clean Air Act (CAA), as amended in 1990 requires that the U.S. Environmental Protection Agency (EPA) submits a study on atmospheric mercury emissions to the U.S. Congress. The Congress directed that the Mercury Study evaluates many aspects of mercury emissions, including the rate and mass of emissions, health and environmental effects, technologies to control such emissions, and the cost of such controls. There are also other activities at a federal and state level.

In Canada, Environment Canada has been involved in preparing emission surveys for mercury emitted from natural and anthropogenic sources. Various strategies for emission reductions have been prepared at a federal and provincial level.

7.2 CURRENT MEASURES TO REDUCE EMISSIONS OF MERCURY IN NORTH AMERICA, INCLUDING POLICY, LEGISLATION AND REGULATORY ACTIONS

This report focuses on mercury control technologies, costs, and financial viability estimates for the following industries:

- ❑ combustion of coal and oil to produce electricity and heat,
- ❑ production of iron and steel, cement, and non-ferrous metals,
- ❑ incineration of wastes, and
- ❑ production and uses of mercury.

These source categories were chosen on the basis of either their source category emissions in aggregate or their potential to be significant sources of emissions. Consideration was also

given to whether a particular source category was a feasible candidate for application of control technology.

7.2.1 Combustion of Coal and Oil

Mercury contained in fuel evaporates during fuel combustion in boilers operating at temperatures above 1100 C. Some of the gas may cool and condense as it passes through the boiler and the air pollution control system. Therefore, most of mercury emissions generated during the combustion process can be controlled by devices added on the installations to remove particles and acidic gases. The most commonly used devices to remove particles from exhaust gases in electric power plants and large industrial boilers are electrostatic precipitators (ESPs) and fabric filters (FFs). Various types of flue gas desulfurization (FGDs) are in use to control sulfur dioxide emissions.

ESPs currently employed in the utility and industrial boilers are not very efficient devices for the removal of mercury from the flue gas as major part of the element leaves the boiler in a gaseous form. Recent literature review of data from various power plants in the United States concluded that ESPs have a median mercury removal efficiency of 32% (U.S.EPA, 1997). It was also concluded that FFs are more efficient in removing mercury from the flue gas stream in power plants as part of the mercury may adsorb onto the fly ash cake collected on FFs. It was estimated that FFs have a median mercury removal efficiency of 42 (U.S. EPA, 1997).

Many of the U.S. and Canadian utility boilers are at present equipped with various types of FGDs. In such cases these boilers have an ESP or a FF before the wet FGD to collect the majority of particulate matter. Information collected by U.S.EPA (1995) indicates that FGD units have a median mercury removal efficiency of about 34% with a range from 18 % to more than 97 % removal.

A dry scrubbing system is also used in the U.S. utility boilers through the application of a spray dryer absorber (SDA). In such cases the SDA system is installed before an ESP or a FF. Tests performed on the SDA/ESP combined control system showed that the mercury removal efficiency was ranging from 23 to 83 % with a median efficiency of 67.3 % (Felsvang et al., 1993). Similar tests carried out for the SDA/FF system showed mercury removal efficiency ranging from 6 to 97 % with a median value of 30% (U.S.EPA, 1995; U.S.EPA, 1997).

The above presented data indicate that currently installed control devices, particularly combined systems of ESP or FFs with FGDs or SDAs can remove over 50 % of mercury from flue gases leaving the utility and major industrial boilers. Data on plant configuration, unit fuel usage, and stack parameters for the United States are available from the Utility Data Institute (UDI)/Edison Electric Institute (EEI) power statistics database. These data are collected on a yearly basis from electric utilities at the U.S. Department of Energy's Energy Information Administration.

7.2.2 Production of Iron and Steel, Cement, and Non-Ferrous Metals

Mercury can be emitted to the atmosphere during the production of metallurgical coke, which is used in iron and steel industry. ESPs or FFs and less frequently wet scrubbers are used in the coke production plants to control emissions, particularly those generated during quenching. This process is performed to cool down the coke and to prevent complete combustion of the coke upon exposure to air. Although no data are available for the performance of the ESPs or FFs in coke production plants it is expected that mercury removal is limited (U.S.EPA, 1993).

The primary sources of mercury emissions from Portland Cement Manufacturing are from the kiln and preheating/precalcining operations. The kiln operations consist of pyroprocessing (thermal treatment) of raw materials which are transformed into clinkers. Raw material processing differs somewhat for the wet and dry processes. Mercury is introduced into the kiln with raw-materials (90% of the material input) and to a minor extent with fuels such as coal and oil which are used to provide energy for calcination and sintering. Other fuels, such as shredded municipal garbage, chipped rubber, petroleum coke, and waste solvents are also being used frequently.

The kiln emissions are controlled in the United States and Canada with either FFs or ESPs but only limited information is available on the efficiency of these devices with respect to the mercury removal. One source indicates (in U.S.EPA, 1993) that ESPs capture about 25 % and FFs capture up to 50 % of the potential mercury emissions as particulate matter. In general, it can be expected that the mercury removal efficiency in kilns will be comparable with the efficiency of the mercury removal by the same devices employed in utility boilers. Concerning the data collection on emissions of mercury from cement plants, cement kiln test reports are reviewed for facilities performing Certification of Compliance (COC) tests in the United States, required of all kilns burning waste derived fuel (WDF).

Primary lead and copper smelters can be regarded as sources of mercury as the element may be present in the ore. Non-ferrous smelters worldwide use high efficiency air pollution control devices to control particle and sulfur dioxide emissions from roasters, smelting furnaces, and convertors. ESPs are the most commonly used devices for removal of particles. Control of sulfur dioxide emissions is achieved by absorption to sulfuric acid in the sulfuric acid plants, which are commonly a part of the smelting plants. Mercury is emitted mostly in a gaseous form and therefore, the ESPs are not very effective in the element removal. The element does not end up in sulfuric acid plants and is, instead, emitted to the atmosphere from the smelter stacks. The amount of these emissions depends on the content of mercury in the ore. This content varies substantially from one ore field to another. Only limited information has been gathered on mercury emission rates from non-ferrous smelters by the U.S.EPA (1993).

7.2.3 Incineration of Wastes

As the content of mercury in wastes varies substantially from one type of waste and the area to another it is very difficult to generalize on mercury emissions from incineration of wastes. Three major groups of incinerators can be considered: municipal waste combustors (MWCs), medical waste incinerators (MWIs), and sewage sludge incinerators (SSIs).

An estimated number of 176 MWCs operating in the United States burn over 31 million tons of trash per year (Cole et al., 1992). More than 85 % of these incinerators with about 99 % of the MWC capacity employ some kind of air pollution control devices. Various types of devices for removal of particles and acidic gases with different removal efficiencies are used according to the information collected by the U.S.EPA (1993). A great majority of mercury is emitted in a gaseous form. Parameters that increase the mercury removal during combustion of wastes are low temperatures at the typical air pollution control devices, such as ESPs, FFs, and scrubbers, the presence of an effective sorbent, such as carbon, and a method to collect the sorbent (Nebel and White, 1991). Recently, a method with the injection of activated carbon or sodium sulfide to the flue gas prior to the ESP or FF is becoming common in Canada, Europe, and Japan, but less so in the United States. This method is expected to remove between 50 and 95 % of mercury from the flue gas in MWCs.

Concerning emission regulations, the EPA's 1991 New Source Performance Standards and Emission Guidelines for MWCs call for new and existing facilities with certain processing capacities to meet certain emission standards for acidic compounds and metals. Regulations authorized by the Clean Air Act Amendments in the United States require that all MWC facilities with a processing capacity equal to or greater than 250 tons per day meet another set of emission standards for acidic compounds and metals. These requirements were proposed in the Federal Register in September 1994. MWCs with capacities larger than 250 tons per day are required to achieve 80 $\mu\text{g Hg}/\text{m}^3$ at 7 % oxygen or 85 % control, whichever is achieved first. Most of these facilities will install carbon injection along with SDA/FF or SDA/ESP. Facilities with processing capacities between 40 and 250 tons per day are required to have duct injection for acidic compounds and an ESP for particles.

At present, about 5000 MWIs is in operation in the United States, including veterinary facilities, nursing homes, and laboratories. It is estimated that at least 90 % of hospitals have an incinerator on-site. It is also assumed that at least larger MWIs are equipped with a simple or more efficient emission control devices. Most of the device systems employed in the medical waste incineration are either wet or dry systems. Wet systems typically comprise of a wet scrubber for controlling the emission of particles in combination with a packed-bed scrubber for removal of acidic gases and a high efficiency mist elimination. Dry systems include ESPs or FFs in combination with the sorbent injection. Concerning the removal of mercury, appearing mostly in a gaseous form, the efficiency of this process is rather limited. An improvement was obtained through adding activated carbon to the sorbent material in the sorbent injection/FF systems (U.S.EPA, 1993).

An improvement was also expected through adding sodium sulfide to the sorbent material in the sorbent injection/FF systems but the U.S. EPA tests showed that this method is not very effective in additional Hg removal. Sodium tetrasulfide is still untested on a commercial basis.

More than 200 SSIs operate in the United States. Most of them are equipped with some type of scrubbing system for the removal of particles. Quite often these systems consist of venturi scrubbers only or a combination of venturi scrubber/impingement scrubber. The latter system seems to be the most efficient in removing mercury, on the basis of comparison of emission factors presented by the U.S. EPA (1993). However, it is difficult to conclude on the efficiency of mercury removal from SSIs using different types of control devices.

7.2.4 Production and Use of Mercury

Mercury can be produced in primary and secondary processes. In primary processes mercury is produced from the ores while in the secondary processes from scrapped mercury-containing products.

At present, mercury is produced in the United States as a byproduct from the mining of gold ores and not from mercury ore. In 1991, there were 8 gold mines in the United States producing metallic mercury as byproduct, while the last mercury ore mine ceased the operation in 1990. On the basis of information from the U.S.EPA (1993), it can be concluded that the mercury emissions from the gold producing plants in the United States are quite well controlled, although no data are available on the amount of these emissions. In general, major sources of mercury emissions within the production process are at locations where furnaces, retorts, and other high temperature sources are employed and where the mercury is removed from the launders. Usually, the emission control installation consists of cyclones, removing larger particles, ESPs for removal of fine particles containing arsenic, mercury and other metals, and various types scrubbers to remove sulfur dioxide and other gaseous substances, including mercury. In the case of high content of mercury in the ore it is necessary to use an activated carbon adsorber bed.

Only about 10 % mercury in the United States is produced in the secondary plants. This production can be accomplished by one of the two general methods: chemical treatment or thermal treatment (U.S.EPA, 1993). The former process results in discharges of pollutants to the aquatic environment, while the thermal process emits various contaminants to the atmosphere.

Control devices in the thermal process based plants are mostly scrubbers but they are very much site-specific. As in the case of other industry branches, primary production plants are usually equipped with more efficient emission control devices than the secondary production plants. However, no details are available to the author on the efficiency of mercury removal from either type of plants in the United States.

Various inorganic mercury compounds are produced in North America using metallic mercury as the starting material. This production presents a potential source of mercury emissions to the atmosphere. No information is available on the amount of these emissions which are controlled mostly at the workplace. Information on removal of mercury from exhaust gases entering the ambient air is not available to the author.

Major uses of mercury include: 1) chlor-alkali production using the mercury cell process, 2) primary battery production, 3) production of measuring and control instruments, and 4) production of electrical lighting, wiring devices, and electrical switches. The use of the mercury cell process to produce chlor-alkali has decreased quite significantly over the past 10-15 years in North America. Already in 1988 this process accounted for only 17 % of all U.S. chlorine production. At present, this contribution is likely much lower. Major points of mercury emission generation in the mercury cell process of chlor-alkali production include: byproduct hydrogen stream, end box ventilation air, and cell room ventilation air. Typical devices/techniques for removal of mercury in these points are: 1) gas stream cooling to remove mercury from hydrogen stream, 2) mist eliminators, 3) scrubbers, and 4) adsorption on activated carbon and molecular sieves. The installation of the above mentioned devices can remove mercury with the efficiency of more than 90 %.

Mercury emissions data from chlor-alkali facilities in the United States can be obtained from Clean Air Act section 114 survey questionnaires (U.S.EPA, 1993). These data are also available from the Toxic Release Inventory (TRI).

The use of mercury in the battery production in the United States has decreased dramatically. Only between 1989 and 1992 the mercury use decreased by 94 % (Bureau of Mines, 1992) and currently only one type of battery, mercuric oxide batteries uses the element. Atmospheric emission of mercury from this source is low compared to other sources. Mercury emission on particles is controlled mostly by FFs, while some mercury vapor emissions from the anode processing and cell manufacturing areas are generally uncontrolled. An application of charcoal filter would likely remove of up to 75 % of these emissions.

Emissions of mercury during electrical apparatus and instrument manufacturing are quite low compared to emissions from other sources. Often these emissions can be controlled by using effective gaskets and seals to contain mercury in the process stream.

7.2.5 On-going Federal and State Activities on Mercury Reduction and Control in the United States

Ongoing programs to control mercury uses, releases, and exposure under a spectrum of environmental laws are summarized at the Federal and State levels (in the EPA document after OECD, 1993). In general, these programs within Federal activities in the United States include:

- environmental media standards, specifying a maximum acceptable mercury concentration for different media,
- environmental source controls regulations that control mercury releases into the environment, including limits on air and water point sources, solid waste disposal restrictions, and requirements for reporting and public disclosure of releases,
- product control regulations for mercury-containing products, e.g. certain pesticides, special paper coatings, pharmaceuticals, cosmetics, and a variety of household products, and
- other standards and programs, for example regulating exposures to mercury in the workplace by establishing Permissible Exposure Limits (PELs).

Considering the scope of this work, the most relevant are environmental source regulations. Mercury and mercury compounds are regulated as Hazardous Air Pollutants (HAPs) under the 1990 Clean Air Act Amendments. National Emission Standards are established for three point source categories of mercury emissions: ore processing facilities, mercury cell alkali plants, and sewage sludge dryers. Major industrial sources may be subject to Maximum Achievable Control Technology (MACT) standards for stationary sources with emissions exceeding 10 tons/year and Generally Available Control Technology (GACT) standards for area sources. New regulations are proposed/implemented for MWCs and MWIs.

Concerning discharges to aquatic environment, mercury is listed as a toxic pollutant and its discharges from certain branches of industry are subject to technology-based effluent limits, under the Clean Water Act.

The U.S. EPA has established under the Resource Conservation and Recovery Act (RCRA) specific classification and disposal requirements for wastes that contain mercury. For example, any solid waste is considered a hazardous substance and prohibited from disposal in RCRA non-hazardous landfills if its leachate contains 0.2 mg Hg/liter or more; land disposal in RCRA hazardous landfills is allowed only after prescribed treatment to reduce mercury in extract to 0.2 mg/liter.

There are also other more general regulations. Any release of 1 pound or more of mercury to the environment in a 24-hour period must be reported immediately to the National Response Center as long as the release is not federally permitted. Certain facilities that release more than a reportable quantity of mercury must immediately report the release to State and local entities. Any release or transfer of mercury by facilities that exceed use or manufacturing thresholds is reportable under the Toxics Release Inventory.

7.3 REVISION OF CURRENT GUIDELINES ON TECHNOLOGICAL MEASURES

A broad review of the abatement techniques for heavy metal emissions from major industrial categories has been prepared for the UN ECE Task Force on Heavy Metals (ECE, 1994). The review is based on the concept of best available technology (BAT), defined as the latest stage of the development of processes, of facilities or of methods of operation which indicate the practical suitability of a particular measure for limiting emissions. In determining whether a set of processes, facilities, and methods of operation constitutes the best available technology in general or in individual cases, special consideration is given to:

- ❑ comparable processes, facilities, or methods of operation which have been recently tried out with successful result,
- ❑ technological advances and changes in scientific knowledge and understanding,
- ❑ the economic feasibility of such technology,
- ❑ time limits for installation in both new and existing plants,
- ❑ the nature and volume of the effluents of concern, and
- ❑ the precautionary principle.

The review concluded that a total dust retention of more than 99.75 % in major stationary sources, such as coal-fired power plants, smelters, cement kilns, and incinerators can be obtained with the use of ESPs and FFs. The contents of heavy metals, including mercury on particles in the flue gas can be reduced by at least 95.0 to 99.0 %.

Various techniques were proposed for capturing gaseous mercury from the flue gas. The application of selenium filter is proposed as a dry media process, which can be applied at both steel and non-ferrous metal smelters. The volatilized mercury is reacting with red amorphous selenium forming mercury selenide. The mercury reduction is never less than 90 %.

Selenium scrubber is a wet media process for removal of fairly large quantities of mercury from the flue gas. The gaseous mercury reacts with activated amorphous selenium, which is circulating in a scrubber with a 20 to 40 % sulfuric acid. The mercury removal efficiency is between 90 and 95 %. However, at low incoming Hg concentrations such as those seen in several utilities the removal efficiency can be less than 90 %.

Carbon filter is another dry media process. The mercury reduction efficiencies of 90 to 95 % have been obtained during measurements at one non-ferrous metal smelter in Sweden.

Lead sulfide process has also been recommended for removal of mercury. The flue gas containing mercury passes through a tower packed with lead sulfide coated balls. This method is used at the Mitsubishi smelter in Naoshima, Japan. The removal efficiency of 99.0 % has been measured.

Mercury content after cleaning of the flue gas with of the above mentioned techniques can be as follows:

	Mercury Content (mg m ⁻³)
Selenium filter	< 0.01
Selenium scrubber	0.2
Carbon filter	0.01
Odda chloride process	0.05–0.1
Lead sulfide process	0.01–0.05

The above mentioned Hg content after using the various control technologies listed above depends on the type of emission source and the uncontrolled Hg rate among other parameters. The UN ECE guidelines do not specify, however, this relationship.

More information on removal of mercury through the application of flue gas control devices is presented later in this work when discussing secondary measures of mercury emission reductions.

Concerning the BAT in chlor-alkali industry, the UN ECE Task Force on Heavy Metals guidelines recommend the membrane process. This technology is now gaining more recognition, although only 5.0 % of the total U.S. chlor-alkali was produced by this method in 1988. The membrane cell process is also more energy efficient compared to the diaphragm cell or mercury cell and produces a higher quality product. A conversion of existing membrane cell and diaphragm cell chlor-alkali plants to membrane cell operation is possible utilizing some of the existing equipment.

7.4 ASSESSMENT OF PRE-TREATMENT MEASURES OF MERCURY EMISSION REDUCTIONS

Fuel washing and fuel substitution are the major pre-treatment measures to reduce emissions of various pollutants from coal combustion processes, including reduction of mercury. There are also some pollution prevention measures, such as materials separation to decrease emissions of mercury from waste incineration.

7.4.1 Coal Washing

Commercial coal cleaning (or beneficiation) facilities, particularly in the United States (e.g. NAPAP, 1990) are physical cleaning techniques to reduce the mineral matter and pyritic sulfur content. As a result, the product coal has a higher energy density and less variability (compared to feedstock coal) so that power plant efficiency and reliability are improved. A side benefit to these processes is that emissions of sulfur dioxide, as well as other pollutants including mercury can be reduced. The efficiency of this removal depends on the cleaning process used, type of coal, and the contaminant content of coal. Basic physical coal cleaning techniques have been commercial for over 50 years.

The cleaning of coal takes place in water, in a dense medium, or in a dry medium. Physical cleaning processes are based on either the specific gravity or surface property differences between the coal and its impurities. Jigs, concentrating tables, hydro-cyclones, and froth flotation cells are common devices used in current physical coal-cleaning facilities.

The mercury concentrations in the raw coal, the clean coal, and the present reduction achieved by cleaning have been presented by Akers et al. (1993) for coals from various regions in the United States. The removal efficiency ranged from 0 to 60 % with 21 % as average reduction. This efficiency is highly dependent on the type of coal and chloride content of the coal.

Concerning other fuels, the cleaning of crude oil occurs mostly through the residue desulfurization (RDS). However, the content of Hg in crude oil is usually very low and RDS is an inefficient method to even lower this content.

7.4.2 Fuel Switching

The following options of fuel substitution are often considered in the electric utilities:

- switching from high- to low-sulfur coal burnt in applicable coal-based generation (including switching directly from high-sulfur to low-sulfur supplies, blending high- and low-sulfur coal, cleaning high- and medium-sulfur coal, or a combination of cleaning and blending),
- increasing the use of natural gas, or oil, and
- increasing the use of alternate fuels or importing electricity to meet base load electric-generation requirements.

The two latter methods are the most interesting with respect to the reduction of mercury emissions. The substitution of coal by coal bed methane to produce heat and electricity would result in decrease of emissions of various air pollutants, including mercury. The following action would be needed in the case of the substitution:

- the modernization of existing utility and industrial heat producing plants,
- the development of new methane burning boilers, and
- the modernization of coal mines with respect to the better exploitation of coal bed methane.

Lower emissions of mercury from MWCs and MWIs can be achieved through a process called product substitution. Although this substitution is potentially applicable to a wide range

of components, batteries have received the greatest attention because of their significant contribution to total mercury content in municipal and medical wastes. Two initiatives were undertaken in order to reduce the amount of mercury used in battery manufacturing:

- an initiative towards reducing and eventually eliminating mercury in household batteries, and
- development of alternatives to mercury-zinc batteries, where small size and constant current supply are critical.

An important issue in this respect is State/ Provincial legislation prohibiting the sale of certain Hg-containing products, requiring manufacturer take back of Hg-containing products (except lamps), and requiring all medical facilities to segregate waste products containing Hg to the level of about 1 ppm. One additional HgO button battery/ ton of medical waste doubles the Hg concentration.

The applicability of the product substitution to other areas should be based on technical and economic feasibility. For example, reducing or eliminating the use of mercury in lighting systems could result in continued use of less efficient technology thereby requiring increased electricity generation and associated air emissions.

7.5 ASSESSMENT OF PRIMARY MEASURES OF MERCURY EMISSION REDUCTIONS

Primary measures of emission reduction include solutions where emission reduction occurs at emission generation point, e.g. application of various modifications of combustion process may reduce emissions from a given burner. Technological modifications in chlor-alkali industry have already been discussed in this report.

7.5.1 Non-conventional Combustion Technologies

Non-conventional methods of combustion, such as fluidized bed combustion (FBC) were found to generate comparable or slightly lower emissions of mercury and other trace elements compared to the conventional power plants (e.g. Carpenter, 1979, Abel et al., 1981). However, a long residence time of the bed material may result in increased fine particle production and thus more efficient condensation of gaseous mercury. Tests carried out in the former Federal Republic of Germany have shown that the residence time of the bed material can be regulated by changing the operating conditions of a given plant, the reduction of combustion temperature, coal size, moisture content, and bed flow rates (Munzner and Schilling, 1985). A literature review of information on the influence of various FBC techniques on emissions of trace elements has been presented by Smith (1987).

Quantities of atmospheric emissions from waste incineration depend greatly on the type of combustor and its operating characteristics. The mass burn/waterwall (MB/WW) type of combustor is often used. In this design the waste bed is exposed to fairly uniform high combustion temperatures resulting in high emissions of gaseous mercury and its compounds. Other types of combustors seem to emit lesser amounts of mercury as indicated by the

comparison of the best typical mercury emission factors for municipal waste combustors (U.S.EPA, 1993). It is also suggested that fluidized-bed combustors (FB) emit smaller amounts of mercury to the atmosphere compared to other sewage sludge incineration techniques, and particularly multiple hearth (MH) techniques.

7.5.2 Low NO_x Burners

Low NO_x technologies are also likely to reduce mercury emission in the exhaust gases due to the lower operating temperatures. Very limited information on this subject is rather inconclusive. While some sources indicate that the reduction can be achieved, preliminary results of staged combustion in atmospheric fluidized bed combustion (AFBC) units indicated that low NO_x had only little effect on trace element emissions (Smith, 1987). It should be noted, however, that low NO_x technologies are far less used compared to the FGD systems.

7.6 ASSESSMENT OF SECONDARY MEASURES OF MERCURY EMISSION REDUCTIONS

Secondary measures include technological solutions to decrease concentrations of pollutants in the flue gas. Major emphasis in this report is placed on the removal of mercury and its compounds by the application of flue gas desulfurization (FGD).

The distribution of trace elements in coal-fired boilers with wet and dry FGD was reviewed by Moberg et al. (1982) within the Swedish KHM project. Halogens, mercuric chloride and selenium dioxide, were removed with sulfur dioxide absorption. Large variations of mercury removal were found, probably due to differences in the behavior of specific mercury compounds. Formation of particles of chloride and sulfate salts was considered to be an important removal mechanism for mercury in the FGD process. This would be promoted by high Cl content in the coal and for mercury sulfate, and by low temperatures combined with the catalytic effect of activated carbon.

Two major types of FGD systems can be distinguished: wet and dry FGDs.

7.6.1 Wet FGD Systems

Distribution of mercury within various streams of the wet FGD system was studied in various countries. As much as 70 % of mercury in exhaust gases has remained in the gas stream after passing through the FGD according to one German study (Gutberlet, 1984). In general, the trace element content of the gypsum and sludge is influenced by the solubility of the elements upstream, the settling behavior of solids in the thickener, and the waste water volume. In the waste water cleaning plant, the solubility of the trace elements is decreased by increasing the pH to the range of 8.0 to 9.5 so the waste water contains only very small amounts of the elements. Their concentrations in the waste sludge are at low levels (e.g. 6 ppm for Hg).

Removal of trace elements from exhaust gases by the wet FGD systems has also been studied in the Netherlands (Meij and Alderliesten, 1989; Meij, 1992), where only pulverized coal-

fired dry-bottom boilers are used, equipped with high-efficiency electrostatic precipitators (ESP) and FGD using a wet lime/limestone-gypsum process with prescrubber. Mostly bituminous coals imported mainly from US and Australia are burnt. In one study (Meij, 1992) the Hg concentration upstream of FGD was $3.4 \mu\text{g}/\text{m}^3$ and downstream was $1.0 \mu\text{g}/\text{m}^3$. The relative distribution of mercury between bottom ash, collected pulverised-fuel ash and fly-ash in the flue gases and in the vapor phase was about 10% on fine particles and about 90% in vapor phase. Flue gases contained 87% of the mercury concentration found in coal, and up to 70% of that was removed by the wet FGD. About 60% of mercury removal takes place in the prescrubber and about 40% in the main scrubber.

In summary, the relatively low temperatures found in wet scrubber systems allow many of the more volatile trace elements to condense from the vapor phase and thus to be removed from the flue gases. In general, removal efficiency for mercury ranges from 30 to 50%.

7.6.2 Dry FGD Systems

Retention of vapor phase mercury by spray dryers has been investigated in Scandinavia and the United States for coal combustors and for waste incinerators (Smith, 1987). The following conclusions have been reached in some of these studies:

- Brosset (1983): Water soluble mercury (40 to 80%) was partly bound in lime slurry and so mostly retained by the lime.
- Bergstrom (1983): 50–70% of the mercury from coal was retained in the ESP ash preceding the FGD spray dryer; 75% of the mercury from coal was retained overall.
- Nilsson (1981): 30–40% of gas phase mercury was retained.
- Karlsson (1986): 52–63% of mercury was removed, with 15–33% retained in the FGD unit (including baghouse).
- Moller and Christiansen (1985): inlet gas phase mercury concentrations of $0.2\text{--}0.7 \text{ mg}/\text{m}^3$ reduced to $0.1\text{--}0.01 \text{ mg}/\text{m}^3$ through the FGD unit.

An excellent retention of trace elements by spray dryer systems implies that fly ash or dry end product might contain high concentrations of mercury. Karlsson (1986) showed that precollection was beneficial for some elements. The pattern for carry over of trace elements from the ESP to the dry end product is complicated by condensation of some constituents and varying degree of enrichment and interactions among the elements. For example, a high Ca concentration led to high As, Cr and Hg concentrations but low concentrations of other elements.

In summary, the overall removal of mercury in various spray dry systems varies from about 35 to 85%. The highest removal efficiencies are achieved from spray dry systems fitted with downstream fabric filters.

It should be added that test results (for both wet and dry FGD systems) carried out before the 1990's are not to be considered as absolutely accurate. Some of the test methods were highly inaccurate, sometimes only capturing a half of the Hg present in the flue gas.

7.7 ASSESSMENT OF NON-TECHNOLOGICAL METHODS OF MERCURY EMISSION REDUCTIONS

Previous chapters of this work have dealt with technological methods to reduce mercury emissions, mostly with the methods often called End-of-Pipe solutions (EOP). An important aspect which needs not to be overlooked is the fact that in most cases EOP control technologies merely transfer the mercury from one form of waste to another. All of the add-on control technologies (carbon filter beds, wet scrubbing, activated carbon injection) generate a contaminated medium which must be disposed of either burning or landfilling, often in a hazardous waste landfill. This creates an additional charge of the pollutants, including mercury to the environment. Non-technological methods have the advantage over the EOP technologies because they do not generate the wastes.

The most known non-technological methods of mercury removal include: energy conservation and pollution prevention solutions. Energy conservation means using less energy to achieve the same level of energy service. Energy services include heat, light, sound, shaft power, and mobility. Decreasing energy production and use will result in the decrease of mercury emissions and provide additional benefits of reducing emissions of sulfur dioxide and other pollutants. A system of credits or vouchers could be developed and presented to the utilities for mercury reduction goals. Demand-side management (DSM) programs should be identified. The DSM refers to actions undertaken by an electric utility to modify customer demand patterns. The DSM programs consist of information dissemination, technologies, or financial incentives and are a component of Least-Cost Utility Planning.

A few solutions of pollution prevention can be presented for mercury, including:

- ❑ materials separation,
- ❑ product content bans,
- ❑ input taxes on the use of mercury in products, and
- ❑ labeling of products.

Material separation deals mostly with the separation of mercury containing materials from the waste streams of MWCs and MWIs. A very small portion of wastes (perhaps less than 1 %) containing very high content of mercury from batteries, fluorescent lights, thermostats and other electrical items needs to be separated from the rest of the wastes, such as paper, plastic, dirt, containing very low concentrations of the element. Several communities in the United States have already implemented household battery separation programs in an effort to reduce mercury in wastes to be incinerated. It is difficult to estimate what portion of batteries is recovered, but the U.S.EPA indicates a range from 3 to 25 % (U.S. EPA, 1991).

Labeling the mercury-containing products would help consumers to select the ones which are mercury-free. This is particularly important for switches and devices that most consumers would not expect to contain mercury.

7.8 COST -EFFECTIVENESS OF MERCURY CONTROLS

Information on investment, installation, and maintenance costs for mercury controls discussed in previous chapters has been obtained from previous projects of the author within the Baltic Sea Environment Program, the available literature on the subject, and pollution control technology vendors. Concerning North America, extensive studies on sources, exposure, and control measures are being carried out at the U.S. EPA. These studies include an evaluation of mercury control technologies, costs, and regulatory issues. The work is still in process and the results are expected soon.

It should be noted that the cost estimates presented in this report are in the 1990/91 US dollars.

7.8.1 Cost-Effectiveness of Mercury Removal from the Flue Gas

Cost effectiveness is an important part of the cost, impact, and benefit considerations associated with the control of air pollutant emissions, including mercury. In general, capital cost and maintenance cost are estimated separately for a given control technology, taking into account the size of emission generation unit, e.g. the size of boiler, type of the control technology employed, volume of the flue gas, the Hg concentrations before and after the control device, and a capacity factor. Capital cost consists of the cost of the purchased equipment, installation of this equipment, and indirect cost. The indirect is often calculated on the basis of the cost of purchased equipment.

More complicated is the estimation of the operating and maintenance cost. There are several parts of the cost which are rather uncertain and are usually assumed. In some countries the operating and maintenance cost is assumed to be a part, for example 4.0 % per year, of the investment cost, being a part of the capital cost (e.g. Amann et al., 1997). In other cases, operating and maintenance cost is calculated using available information and assumptions on costs of operating and supervision labor, maintenance labor and maintenance materials, operating materials, as well as costs of purchased materials, power, disposal, and various taxes. The operating and maintenance cost is annualized. An example of estimates of cost - effectiveness of mercury control measures in utility boilers and waste incinerators is presented in Table 1 after available data from the literature. The purpose for inclusion of this table was to inform the reader about the cost level rather than to give a cost rate for precise cost estimates in certain specific case of mercury control implementation. In the lastest case a thorough analysis of cost effectiveness would be needed. Examples of investment (capital) cost and annualized operating and maintenance cost estimates for power plants in Table 1 are given for a utility of ca. 1000 MW output. Application of carbon filter beds is a very efficient solution to remove mercury from flue gases but it also seems to be one of the most expensive methods; particularly the cost of purchased equipment is very high.

The effectiveness of the activated carbon injection and carbon filter beds in recovering different chemical species of mercury is still in the early stages of investigation. Without the activated carbon injection, a pilot SDA/ESP system removed 95 % of the ionic mercury from the flue gas of a coal-fired power plant (RTI, 1993). Activated carbon injection ahead of the SDA/ESP system would remove 90 % of the total mercury.

Information on total cost of mercury removal from the MWC flue gases in Table 1 is given for small units (a couple of hundred tons of wastes incinerated each day) and larger units (about 10 times more than small units), separately. Again, the employment of carbon filter beds seems to be very efficient but also very expensive solution for mercury removal from MWCs. Concerning the cost of mercury control in MWIs presented in Table 1, these estimates are for two unit sizes of combustors: around 60 and 460 kg wastes per hour. These preliminary estimates have been made for the U.S.EPA report to Congress (e.g. Radian, 1993; RTI, 1993).

Estimates of cost - effectiveness for mercury removal from the flue gas have also been made for other industrial sectors, particularly for non-ferrous metal smelters and chlor-alkali plants. Selenium filters are recommended for the removal of mercury from the flue gas stream upstream of the acid plant in non-ferrous metal smelters. These filters, developed already in the 1970's in Sweden would have removal efficiency of up to 90.0 %. The estimates of the annualized cost indicate a range from US\$ 10.0 to more than 50.0 per 1 tonne of copper produced. In the case of lead smelters this cost is about 50 % lower.

Estimates performed by Eurochlor, an umbrella organization representing the chlor-alkali industry, indicate that the conversion from mercury electrolysis to membrane electrolysis (no mercury involved) would cost about US\$ 1000.00 per tonne of chlorine (Eurochlor, 1993).

7.8.2 Cost-Effectiveness of Other Measures of Mercury Removal

In general, direct abatement methods related to pre-combustion control, such as switch to or blend with fuels, and coal or oil cleaning cannot be recommended due to either low efficiency or high cost when used only to remove mercury. Cost - effectiveness for coal cleaning/beneficiation processes in the United States at the end of the 1980's ranged from US\$ 120.00 to 500.00 per tonne of sulfur dioxide removed, depending on the removal technique used and the type of coal cleaned (e.g. NAPAP, 1990). This method was found more expensive than the switch of fuels. A total retrofit cost of altering a coal-fired boiler for a seasonal use of natural gas has been conservatively estimated to be about US\$ 18000.00 per 1 MW. The cost of the pipeline must be added to the natural gas retrofit costs, ranging from US\$ 75.00 to 175.00 per 1 ft of pipeline.

A total retrofit cost of at least US\$ 42000.00 per 1 kg of mercury removed through the implementation of pre-treatment measures of control was estimated by Pacyna (1992) for the Baltic Sea Environmental Programme.

Table 7.1 - Cost-effectiveness of mercury control measures in utility boilers and waste incinerators

Control Option	Mercury Removal Efficiency %	Costs	
		Investment	Operating and Maintenance
1. Power plant *1			
- ESPs (only)	10	1.6	0.2
- FFs (only)	29	28.9	5.8
- ESP or FF + wet FGD	85	59.0	2.5
- dry absorber SDA+ESP	67	143.0	5.0
- ESP + carbon filter beds	90-95	264.0	62.0
- activated carbon injection +FF	50-90+	34.6	8.1
2. Municipal Waste Combustor (MWC) *2			
- ESP and FFs			
- as above			
- ESP or FF + carbon filter beds	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
3. Medical Waste Incinerators (MWI) *2			
- ESP and FFs			
- as in p. 1.			
- activated carbon injection +FFs	50-90+	56.5/127.0	89.0/84.0
- polishing wet scrubber +FFs	85	400.0	100.0

*1 Investment cost in 1000 US\$/MWh, while operating and maintenance cost in 1000 US\$/MWh * year

*2 Investment cost in 1000 US\$/tonne of waste, operating and maintenance cost in 1000 US\$/1 tonne waste * year. Two estimates are given for large plant/small plant

ESP = Electrostatic Precipitator

FF = Fabric Filter

FGD= Flue Gas Desulfurization

SDA= Spray Dryer Absorber

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