



Mercury in waste in the European Union: sources, disposal methods and risks

Arun B. Mukherjee^{a,*}, Ron Zevenhoven^b, Jens Brodersen^c,
Lars D. Hylander^d, Prosun Bhattacharya^e

^a Department of Environmental Protection Sciences, University of Helsinki,
P.O. Box 27, 00014 Helsinki, Finland

^b Energy Engineering and Environmental Protection, Helsinki University of Technology,
P.O. Box 4400, FIN-02105 Hut, Finland

^c European Topic Centre on Waste, Overgaden Oven Vandet 48E, DK-1415 Copenhagen K, Denmark

^d Department of Limnology, Evolutionary Biology Centre, Uppsala University, SE-752 36 Uppsala, Sweden

^e Department of Land and Water Resources Engineering, Royal Institute of Technology,
SE-100 44 Stockholm, Sweden

Received 15 April 2003; received in revised form 23 January 2004; accepted 12 February 2004

Abstract

Over the recent decades, there has been widespread concern regarding the toxic impact of mercury (Hg) in the ecosystem due to its mobility, volatility and potential for bioaccumulation. Hg in fish and the aquatic environment is also a great problem in the Nordic region of the EU¹ (European Union). Hg is classified as a dangerous chemical in the countries of the EU. Hg in the regulation of waste is regarded as a dangerous substance which, when contained in waste, is one of the properties, leading to a classification of waste as hazardous. Estimation of the quantity of Hg in waste within the EU countries is an important task although still incomplete.

In this present study, Hg in waste in the EU has been estimated at around 990 metric tonnes (t) (including coal combustion products, landfills, chlor-alkali waste and incinerator slag) for the year 1995, and it is suggested that if complete information was available for the 15 member states, the amount would be 2–4 times larger. During the 1990s there were 45 Hg cell chlorine facilities in the EU and the amount of Hg in chlorine (Cl₂) was calculated at 95.2 t based on 14–17 g Hg t⁻¹ of Cl₂ capacity. The waste from coal-fired power plants in the EU member states contained about 16.5 t of Hg, which was transferred to products for road construction, and other industrial uses or

* Corresponding author. Fax: +358-9-191-58462.

E-mail addresses: arun.mukherjee@helsinki.fi (A.B. Mukherjee), ron.zevenhoven@hut.fi (R. Zevenhoven), etcw-jb@mst.dk (J. Brodersen), lars.hylander@ebc.uu.se (L.D. Hylander), prosun@kth.se (P. Bhattacharya).

¹ EU means EU-15, i.e. the 15 member countries at the time of writing this paper (early 2003).

stored in landfills. This Hg can then be exchanged between the atmospheric, aquatic and terrestrial compartments. Hg is occasionally recovered from waste, but this is often discouraged for economic reasons. Recovery units are found, for example, in Germany, France, Austria, and Sweden. The total amount of secondary Hg recovered from waste is not known. Metallic Hg and Hg-bearing waste are exported and imported from the EU member states, except for export from Sweden, which is banned by national legislation.

The use of Hg in lamps and batteries is declining, and the Nordic countries, Germany and Austria have stringent regulations on the use of amalgam and Hg thermometers. It is found that 18% of municipal solid waste generated in the EU is burnt in incinerators, in order to decrease the volume. 88 t of Hg enter into the landfills of the EU through waste and residues from waste incineration. Prevention of the generation of hazardous waste containing Hg is one of the most challenging tasks for the EU, with regard to sustainable waste management.

© 2004 Elsevier B.V. All rights reserved.

Keywords: Hazardous waste; Mercury; Risk assessment; European Union

1. Introduction

1.1. Motivation

This article presents work done to give an overview on the pan European situation concerning mercury (Hg) spread to the environment. Hg is one of the heavy metals with well-known adverse effects on humans and the environment. Countries and international organisations have both done a lot to prevent the adverse effects either by setting up standards for maximum content of Hg in food or by restrictions on the use of Hg. Surprisingly no overview of Hg in waste or Hg loss to the environment can be established easily, only sporadic information for a few countries exists or the information does not exist at all.

1.2. Materials flow

Materials that are extracted, produced, transported, utilised, and recycled have significant influence on the productivity, impact, and quality of our environment. Hence, it is important for present society to study flows of metals and materials from the beginning of mining, smelting, processing and creation of target products as well as their uses and reuses, disposal, and recycling. During the last decade, such studies have been made in the United States on arsenic, vanadium, mercury and many other metals (Hilliard, 1994; Loebenstein, 1994; Sznopce and Goonan, 2000), but very little focus has been put on material flows in Europe up to the Sixth Environment Action Programme (European Communities, 2001a; EU²), although metal and material production and their uses play an important role in the economy of Europe and the world. In our study, Hg flows in the waste of the EU-15 countries have been examined, and this flow pattern is shown in Fig. 1. The necessity to track the flow of

² EU commission submitted a communication to the council and the European Parliament: "Towards a Thematic Strategy on the Sustainable use of Natural Resources" COM (2003) 572 final. This includes a strategy to avoid further contamination of the European Environment with Hg and other heavy metals.

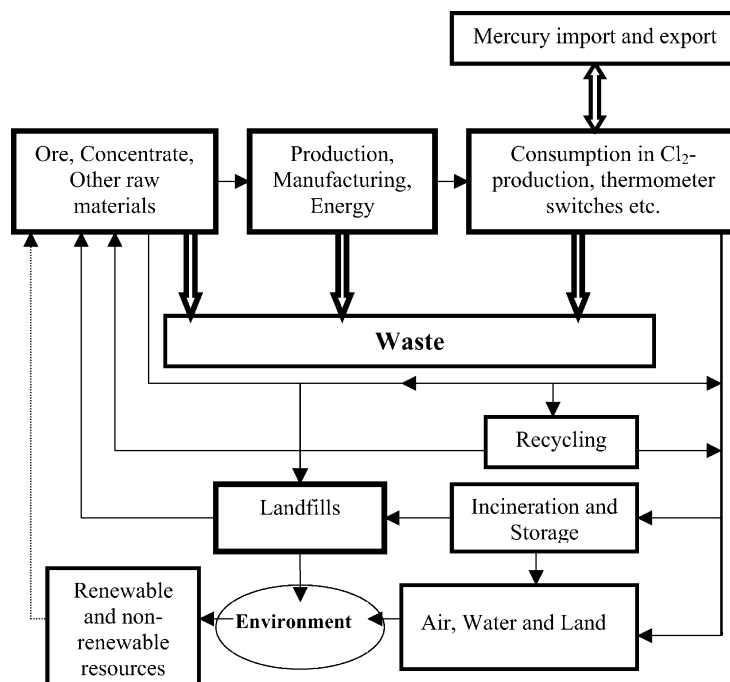


Fig. 1. Model of mercury flows in waste in the European Union.

Hg in the environment and its effects on human health arises as a result of its highly toxic properties.

1.3. Mercury in waste

Human activities are responsible for the dispersion of metals and other elements which have been concentrated over the geological time scale. It is increasing in a linear scale since the industrial revolution (Bergbäck and Lohm, 1997; Renberg et al., 1994) and the anthropogenic pollution of Hg, Cd, Pb, and As are of great concern. Hg in waste can be a significant source of Hg releases to the environment. Consequently, inventories of Hg in waste are important in our society. Any waste production whether hazardous or non-hazardous is governed by the yield and consumption of goods and their recycling in society. The materials and energy often locked in waste resources can be recovered, recycled, or reused, but due to cost structure, wastes are sometimes dumped in landfills. Different compounds of waste contain both useful and harmful metals, and organic and inorganic compounds which in the long run may be converted into hazardous compounds in the environment.

Europe is one of the major chemical-producing regions of the world (EEA/UNEP, 1998; EEA, 1999a), resulting in Hg-bearing waste. The effect of Hg on human health and the environment depends mainly on the toxicokinetics of its chemical forms, e.g. elemental

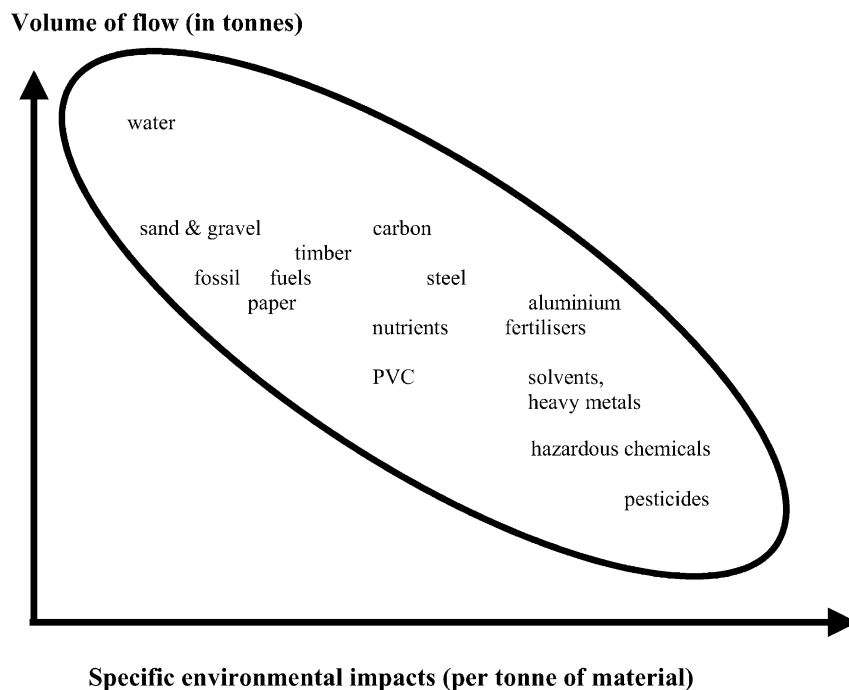


Fig. 2. Material flow and specific environmental impact: qualitative and quantitative aspects of waste (redrawn from EEA, 1999a).

Hg (Hg^0), inorganic Hg (HgCl_2) and organic Hg (methyl-Hg most common in nature). Due to its low boiling point (357°C at 1 atm), this metal evaporates and after entering into the aquatic environment, inorganic Hg is transformed into methyl-Hg compounds through microbial activities and bioaccumulates in aquatic food chains (Berlin, 1986; Guimāraes et al., 2000; Horvat et al., 1993; Watras and Huckabee, 1994). Once methyl-Hg enters into humans, it causes nervous disorders, cancer, brain damage, difficulty in vision, hearing, walking, tremors, coma and even death (Barregard et al., 1999; Harada, 1995; IPCS/WHO, 1990, 1991; Ishihara and Urushiyana, 1994). The history and effects of the release of toxic compounds among the fishing community in Minamata Bay, south of Japan attracted global attention (D'Itri and D'Itri, 1977; D'Itri, 1994; Ellis, 1989; Harada, 1982; Mishima, 1992). Fig. 2 indicates quantitative and qualitative aspect of waste. For a selective type of waste, minor volume of waste is more toxic to the environment, and is difficult to collect and separate from big quantities of waste (Steurer, 1996). Hence, sources and material flow for Hg in waste from one medium to another should be clarified and policies be directed toward minimising environmental impacts of Hg in waste by adjusting some aspect of particular material flow at production (Sznoppek and Goonan, 2000).

There is no separate information in which one can identify the flow of Hg in waste in the EU-15 countries in the European Environment Agency documents on waste and hazardous waste for the EU (EEA, 1999b, 2001a). Member states in the Mediterranean

region supplied inadequate information on Hg in waste. Hence, it is necessary to identify the generation sources, stockpile, recycling, and flow of diversity of Hg in waste in the EU region as top priority has been focused on this metal to protect air, water and soil ecosystems as dictated in Art 7.2 of the Framework Directive (Council Directive, 1996) (European Communities, 2001b). Life cycles analysis of Hg uses will provide more information on its releases from mining and smelting, transport, Hg in waste disposal and recovery, and product manufacturing.

This report is based on information supplied by the European Commission, Ministry of Environment of EU-15 countries, and other organisations in Europe. Information from the US Environmental Protection Agency and the US Geological Survey is included, since data on Hg in waste for the EU countries were incomplete.

1.4. Classification of hazardous waste

It is important that the classification of hazardous waste in different countries is based on a common classification in waste statistics regulation (European Communities, 2002). Classification of sources for waste is to be NACE (general industrial classification of economic activities within the European Communities). These will provide constructive information on sources and process orientation so that decision makers can take action on transboundary movements of hazardous waste, waste minimisation and cost effective cleaning technology for the particular process. In Table 1, different classification of hazardous waste has been applied. The Basel Convention for the Control of Transboundary Movement of Hazardous Waste and their Disposal entered into force on 5 May 1992. The main objectives of the

Table 1
Total generation of hazardous waste in the European Union (EEA, 1999b)

Country	Year	Total generation (t)	Classification
Austria	1995	577,000	National
Belgium	1994	776,000	Basel
Denmark	1995	250,000	National
Finland	1992	359,000	National
Finland	1997	485,000 ^a	National
France	1990	7,000,000	National
Germany	1993	9,100,000	National
Greece	1992	450,000	National
Ireland	1995	248,000	National
Ireland	1996	327,862 ^b	National
Italy	1995	2,708,000	HWL (hazardous waste list)
Luxembourg	1995	180,000	National
The Netherlands	1993	1,520,000	National
Portugal	1994	1,356,000	Basel
Spain	1994	3,394,000	Basel
Sweden	1985	500,000	Basel
United Kingdom	1992/1993	2,299,000	
United Kingdom	1993/1994	1,844,000	Basel

^a Finnish Environment Institute (pers. comm., 2001).

^b EPA/Ireland (1999).

Basel Convention are (ERM, 2000):

- to reduce the transboundary movements of hazardous waste to a minimum;
- to dispose of hazardous waste near their sources of generation;
- to minimise the quantity and magnitude of hazardous waste generated.

A substance oriented classification as in waste statistics (European Communities, 2002) will furnish on overall amounts, treatment methods and so on. Detailed classifications of hazardous waste in EU countries can be read from the publication of the European Environment Agency (EEA, 1999b, 2001b).

However, in this study Hg in waste estimation, national clarification (e.g. information are provided by the individual state, companies, and organisations) has been adopted. It is clear that volume of hazardous or Hg in waste depend on the industrial set up in a country or region. Hg in waste originate generally from the following (Huse et al., 1999):

- mining waste;
- metal production;
- chlorine plants;
- used products (batteries, thermometers, light sources, instruments, and electronic equipment);
- laboratory waste;
- sewage sludge;
- residues and ashes from incineration;
- paints;
- pesticides, anti fouling agents, polluted sites and soils;
- landfills;
- cement production;
- paper and pulp industry;
- phosphate production; and
- cremations.

2. Production and uses of mercury in the European Union

2.1. Production

The Hg mines in the EU are situated in Italy and Spain, together having estimated deposits of 159 kt of cinnabar (HgS) (USGS, 1999). In Italy, the T. Amiata mines situated in the Tuscany region, were closed already by the Romans to protect the workers and the environment. They were reopened for the production of Hg in 1868. However, these mining and smelting activities stopped completely in 1980 (Ferrara, 1999), whereas the mines in Almadén, Spain, are still active. The production capacity of Hg is reported to be 3.5 kt per year, but actual production has been cited by Hylander and Meili (2003) as 237 t for 2000. In Finland, Outokumpu Zinc Ltd. on the west coast of Finland recovers virgin Hg during roasting of zinc concentrate and the amount varied from 98 to 76 t between the years 1993 and 2000. Thus, total production of primary Hg in the EU dropped from 740 t in 1993 to 313 t in 2000, whereas world primary Hg production was reported to be 1800 t for 2000

Table 2
World primary mercury production (t) (Scoullos et al., 2000)

Country	1993	1994	1995	1996	1997	1998	1999	2000 ^a
Algeria	459	414	292	368	447	224	200	240
China	529	470	780	510	830	230	200	200
Finland ^b	98	83	90	88	90	80	80	76
Kyrgyzstan	1000	379	380	584	610	620	620	600
Mexico	12	12	15	15	15	15	15	25
Russia	60	50	50	50	50	50	50	–
Slovakia	50	50	0	0	0	20	0	0
Slovenia	0	6	0	5	5	5	0	0
Spain	643	393	1497	862	863	675	600	237 ^c
Tajikistan	80	55	50	45	40	35	35	40
Ukraine	50	50	40	30	25	20	–	–
United States	400	400	400	400	400	400	400	15
Other countries ^a	– ^d	223	200	–	–	830	380	448
Total	3381	2585	3790	2960	3380	3200	2580	
Estimated by Hylander and Meili (2003)	3000	2000	3300	2800	2500	2000	2100	1800

^a Cited by UNEP (2002).

^b Finnish Hg production between 1993 and 2000 was reported by Outokumpu Zinc Ltd., Kokkola, Finland.

^c Reported by the Spanish mercury mines.

^d Not available.

(Hylander and Meili, 2003) (Table 2). The demand of global Hg consumption is decreasing, but Hg mine production is dominated by a few countries such as Kyrgyzstan, Spain, China, and Algeria (Hylander and Meili, 2003; UNEP, 2002).

In addition to primary production, Hg is also recovered from waste such as batteries, medical thermometers, instruments, lamps, and also from the gas streams of the non-ferrous metallurgical industry. Recycled Hg has played an important role in the EU countries in recent decades. Hg recovery technologies are available in most EU countries, but is not always practised for economical reasons. The number of Hg recovery companies is not clear in the EU countries. In this study, it has been noted that if a recycling company is identified, it is still impossible to get Hg recovery data except for a few companies in Germany and The Netherlands. An available information for recovery, export and import of Hg in waste for selected of countries (through environmental agency of the individual country) is given in Table 3. It is observed that substantial amounts of Hg in waste are imported and exported by Belgium; Rotterdam is also a gateway from where Hg is exported and imported. Between 1990 and 1994, The Netherlands exported 120 t of Hg to Brazil and a large part of Spanish Hg production is exported to the developing and other countries via the free port of Rotterdam (Hylander, 2001a; Soares and Mello, 1994). Fig. 3 indicates the Hg trade from western Europe, north America, Africa, and Russia to other regions of the world.

2.2. Uses

Hg use in the society has decreased because of its toxicity (Hylander and Meili, 2003), but still it is used in chlorine production, domestic and industrial batteries, thermometers,

Table 3

Mercury waste generated, processed, exported, and imported in selected EU countries based on the information received from individual states

Country	Waste generated/Hg recovered/stored (t a^{-1})	Waste/or Hg exported (t a^{-1})	Waste/or Hg imported (t a^{-1})	Year
Austria	6.0 (Hg)	1120 + solid residue ^a	5.8	1999
Belgium	0	1388 (waste)	312 (waste)	1999
Denmark	0	6.5 (Hg)	2.5 (Hg) + 100 Hg contained soil	1990
Finland	0	151 (Hg)	0.5	1990
France	0	87	0	1993
Germany	143 (Hg)	87 (Hg)	0	1993
Ireland	180 (Hg-waste)	180 (Hg-waste)	0	1996
The Netherlands	13011 (waste)/110 (Hg)	110 (Hg)	?	1999
Sweden	610 (stored)	0	4–5 (Hg in amalgam)	1990

^a Residue from flue gas purification at waste incinerators containing 500–1000 mg Hg kg^{-1} .

instruments, electric switches, gauges, manometers, barometers, fluorescent lamps, and dental amalgam. In Sweden, the sale of clinical thermometers containing Hg is forbidden since 1992, whereas the sale of Hg containing switches, apparatuses, instruments, and other equipment was banned from 1993 (SFS, 1991; Svensk författningssamling, 1991). In recent years, amalgam use for tooth filling has been discouraged in European society and has been replaced by improved carbonations of metal oxide and silica nanoparticles in polymeric materials (organic composite materials) (improved polymeric composite materials

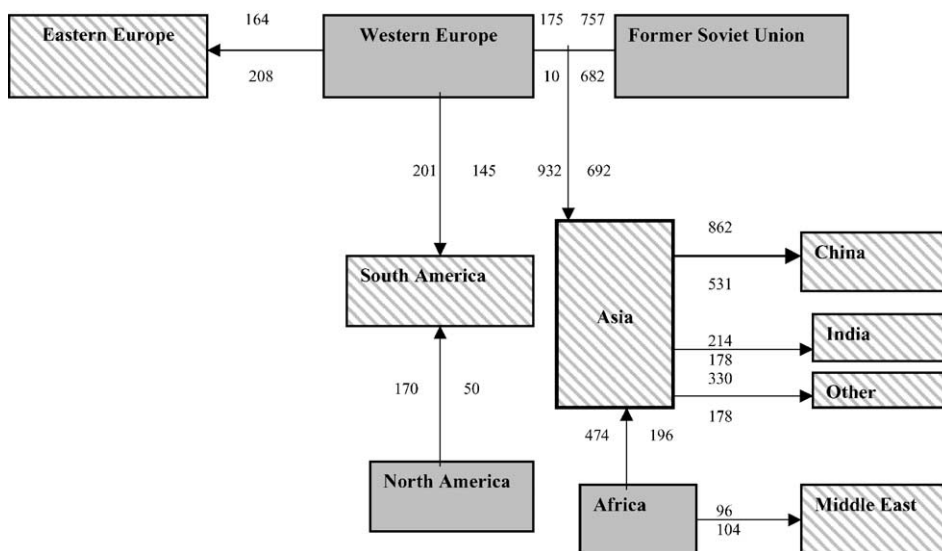


Fig. 3. World export and import of mercury wastes in the 1990/1996 (t a^{-1}). Grey blocks indicated exporters of mercury and the strip blocks indicated importers of mercury. Data suggests that mercury export and import has been reduced by 33% between 1990 and 1996 (Sznopce and Goonan, 2000).

for dental fillings: <http://www.nasatech.com/Briefs/May01/MSC22842.html>). In Denmark, for example the consumption of Hg in dental filling has been reduced from 3.1 t in 1983 to 0.9 t in 2000/2001 (Heron, 2001; Maag et al., 1996). Many countries of the EU, still use Hg in pesticides, latex paints, pigments and tanning, catalytic Hg compounds and use of Hg for etching steel and for toys (UNEP, 2002).

3. Mercury containing waste in the European Union

3.1. Overview

The quantity of waste from all sources generated in the EU is apparently increasing, and in 1995 the estimated amount was 3500 kg per capita in EU. In 2003 the estimated waste generation from west Europeans is expected to be 3800 kg per capita according to EEA (2003) corresponding to 1425 Mt (assuming 375 million habitants). The estimated waste generation was totally about 1300 Mt for 1995 (Christiansen and Munck-Kampmann, 2000), whereas 27–36 Mt of hazardous waste were generated per year of which 1.4 Mt were exported to other countries (EUROSTAT, 1999; OECD, 1997). Total volume of hazardous waste is increasing in most member states, but in some countries such as the UK it is decreasing (Table 1). Increasing or decreasing volume of hazardous waste is partly a result of changed definitions and legislation for hazardous waste, and also unharmonised national and international classifications of hazardous waste (van Beusekom, 1999; OECD, 1997; EEAb). The large increase for Austria, Denmark, Finland, Ireland, Luxembourg and Catalonia (Spain) is due to the introduction of new hazardous waste lists in the European Waste Catalogue. The amount of per capita hazardous waste in EU countries varies between 18 and 481 kg per annum. Intensive waste treatment activities in Belgium (Flanders) have caused an increase in hazardous waste production (276 kg per habitant). Luxembourg, is highest at 481 kg hazardous waste generated per habitant, which was due to large site rehabilitation and decontamination activities up through the 1990s (van Beusekom, 1999).

Table 4 indicates the Hg in waste in 11 of the EU countries, Luxembourg, Greece, Italy, and Portugal, being excluded as no information is available from these four countries. None of the countries submitted information on the total Hg in amalgam. In this case, Hg has been estimated considering 45–50% of Hg in amalgam. In Table 4, information for Hg in waste is often missing for incineration processes, chlorine production, power plants, mining activities, and laboratory waste. Most countries (except Belgium and Spain) have kept good records for items such as batteries, lamps and amalgam waste. Estimated Hg in waste from selected sources for 11 EU countries at the end of second millennium was 745 t (Table 4). In our study, estimated Hg in waste for Denmark was 8.84 t, whereas Maag et al. (1996) estimated 7.98 t for 1992/1993. This difference is due to presence of Hg in instruments and electronic switches.

3.2. Batteries

Consumption of the different kinds of batteries has increased, but the Hg content has decreased. Nowadays, in general, alkaline-manganese batteries contain 0.025 wt.% Hg,

Table 4

Estimated mercury content in waste (t a^{-1}) in the EU member states (excluding Luxembourg, Italy, Greece and Portugal) at the end of old millennium (information for waste amounts were supplied by individual countries)

Source	Austria	Belgium ^a	Denmark	Finland	France	Germany	Ireland	Netherlands	Spain (Catalonia)	Sweden	UK	Grand total
Batteries	0.9	1.09	1.6	1.0	6.8	13	11.45	15.7	14.4	1.0	4.4	
Lamps	0.06	0.009	0.15	0.12	0.2	1.37 ^b	0.03	0.083	0.002	0.3	4.0	
Amalgam	5.0	– ^c	1.0	0.42	9.0	29.0	0.5	11.0	–	0.7	10.5	
Inc. waste	30.2	–	1.8	–	–	–	–	15.0	–	–	14.4	
Sewage sludge	0.34	0.18	0.22	0.21	2.67	2.66	0.03	0.57	0.4	0.45	2.86	44.5 ^d
Thermometers	–	0.01	1.75	0.2	9.0	–	–	–	1.0	1.5	1.3	
Instrument	–	–	2.2	0.54	0.4	5.0	–	–	–	–	–	
Sludge, Cl ₂ production	0	–	0	–	–	–	–	2.0	–	39.0	–	
Power plants	–	–	–	–	–	–	–	–	–	7.0	22.8	
Lab waste	–	–	0.12	0.01	0.9	3.0	–	–	–	–	3.7	
Metal industry	–	–	–	0.09	18.0	–	–	4.75	123 + 224 ^e	9.5	10.20	
Total	36.5	1.29	8.84	2.59	46.97	54.03	12.00	49.1	362.48	59.45	118.66	752
Year	1999/2000	1993	1996	1996	1993	1993	1996	1997/1999	1999	1996	1996	
Reference	1 + EEA (2002)	1 + EEA (2002)	Huse et al. (1999) and EEA (2002)	Huse et al. (1999) and EEA (2002)	2 + EEA (2002)	1 + 3 EEA (2002)	1 + EEA (2002)	1 + EEA (2002)	1 + Anon. (2000)	1 + EEA (2002)	1 + EEA (2002)	

1: national submission; 2: Genie Urbain-Genie Rural (1999); 3: Maxson and Vonkeman (1996). Sewage sludge values are based on 1996/1997.

^a Estimation is based on: batteries; 50% contain Hg-oxide (Hg content 30%) and the rest (0.7% Hg); weight of a lamp 250 g containing 15 mg Hg/unit; thermometer: weight 50 g containing 1 g Hg (Huse et al., 1999).

^b 1.37 t of Hg in lamps have been estimated as follows—fluorescent discharge lamps: 15 mg Hg/lamp; compact lamps: 5 mg Hg/lamp; high pressure Hg-vapour: 30 mg Hg/lamp; metal halide: 30 mg Hg/lamp; high pressure sodium: 25 mg Hg/lamp; 90 M units (Genest, 1997). Holland—batteries: half of the total amount (2700 t) contain 0.2% Hg and the rest amount contain 1.0% Hg (Bjønstad and Linde, 1994). Electrofilter sludge contains 2900 mg Hg/kg sludge (dry matter); residue contains 20% Hg; jarosite waste from Zn-plant contains 50 mg Hg/kg; amalgam waste contains 50% Hg (Meijer, 2001); weight of lamp was estimated by multiplying 250 g/lamp; total Hg in lamps: 5.5×10^6 units \times 15 mg = 0.083 t.

^c Not available.

^d United Kingdom: Hg in municipal waste.

^e Mercury wastes and 224 t of Hg in wastes generated by Mayasa Company (Anon., 2000).

Table 5
Detailed study of mercury flow through batteries in France, 1996 (Genie Urbain-Genie Rural, 1999)

Type	Batteries used (t)	Hg (%)	$\mu\text{g Hg g}^{-1}$	Hg (t)
Cylindrical				
Acidic	12340	0.05	500	2.5
Alkaline	9600	0.10	1000	9.6
Button cell				
MnO ₂ -Zn	10	0.5	0.05	
Air-Zn	16	1.0	0.16	
Ag ₂ O-Zn	16	0.5	0.08	
HgO-Zn	18	30.0	5.4	
Total	22000	0.081	17.79	

Note: t, metric tonnes.

while manganese oxide batteries do not contain any added Hg (TemaNord, 1999). Hg-oxide batteries have been replaced by zinc–air, lithium and other low-Hg batteries in many EU countries. But the use pattern of low and high Hg content batteries is not clear from one country to another. Table 5 indicates the detailed flow of Hg in the battery sector in France. In this study, the difference from total Hg in batteries for France (Tables 4 and 5) is explained by the fact that total quantity of batteries and their Hg concentration were not available from the administrative section of the country during the course of the study, which resulted different results. In our study, the total amount of Hg in batteries used in 11 EU countries has been estimated 71.34 t a^{-1} . In the past, Maxson et al. (1991) estimated for EC countries to 40 t in 1991, and 79 t in 1989.

In recent years, legislation in the form of the Mercury Containing and Rechargeable Management Act was established in the OECD (Organization for Economic Co-operation and Development) countries (Morrow, 1997). Hg and other heavy metals containing battery collection schemes, recovery technologies and information campaigns were developed. Generally, recovery of Hg is more expensive than dumping the Hg-containing waste at landfill sites. Due to lack of a suitable facility, especially when the volume of battery waste is small, this waste is exported to another country for metal recovery.

3.3. Lamps

The use of Hg lamps in society is increasing, but Hg amount in individual lamps has decreased. Energy costs and saving campaigns motivate people to use energy saving types of lamps. It is reported that the consumption of Hg for lighting purposes in Nordic countries remained the same for the last ten years (Rasmussen, 1992). Estimated Hg uses (in g) per person stemmed from lamps in Denmark, Finland, the UK and Sweden were 0.02, 0.02, 0.07, and 0.11, respectively. In the US, Hg use in lamps, electrical equipment and instruments has increased from 204 t in 1989 to 272 t in 1992, an increase of 30% (Sass et al., 1994).

3.4. Mining and smelting industry

The Mayasa mining and smelting company in Spain produces hundreds of metric tonnes of virgin Hg per year and very little is known about Hg in waste generation and waste handling at Mayasa. Recent studies indicate that the Mayasa facility produces 2 kt of waste per year containing 11.2% of Hg and management has decided to build an incinerator to recover the Hg from the waste (Anon., 2000). An appeal has been made to the Environmental Commissioner of the EU to stop the mining and smelting activities of Hg ores (Hylander, 2001b). There is no detailed information on Hg in waste stemming from metallurgical industry, waste incinerators, and mining activities in Almadén and the EU countries except Sweden (Table 3).

3.5. Mercury in coal combustion products

Worldwide coal shares 37% of the total fuel used in the energy sector (USDoE, 1998). Strict regulations have been applied to reduce Hg emission from European and other countries, but coal-fired power plants are still responsible the largest amount of Hg emitted to the ecosystem. Coal combustion products (CCPs) from power plants are generally coal fly ash, bottom ash, boiler slag, fluidised bed combustion (FBC) residue and flue gas desulphurisation (FGD) residue. Most of the ashes and other waste are used in the building sector, as construction material for civil engineering, and the restoration of open cast mines, quarries and pits. There is lack of information from individual states regarding Hg in fly and bottom ashes from burning of fossil fuels for heat and electricity production.

The production of CCPs in the EU-15 countries decreased from 57 Mt in 1993 to 55 Mt in 1999 due to installation of better power plants and the market situation in the electricity industry (vom Berg et al., 2001) and based on model calculation mean Hg concentration in the CCPs has been estimated to be $0.3 \mu\text{g Hg g}^{-1}$ (Meij et al., 2001). Considering the mentioned information, the distribution of Hg in CCPs is given in Table 6.

3.6. Chlorine production in the European Union

After metal manufacturing and production, the chemical industry is the second largest industry in the world (according to the public information collected by ICI Chemicals and Polymers; cited by EEA/UNEP, 1998; Lindley, 1997). For over century, the Hg cell process

Table 6
Distribution of mercury in coal combustion products, 1999 (after vom Berg et al., 2001)

Source	Amount of CCPs (Mt)	Hg in CCPs (t)
Construction industry and mining (55.6%)	30.58	9.17
Restoration, mines and pits (33.1%)	18.21	5.46
Disposal (9.2%)	5.06	1.52
Stockpiles (2.1%)	1.155	0.35
Total	55	16.5

Hg concentration in CCPs: $0.3 \mu\text{g Hg g}^{-1}$ (Meij et al., 2001).

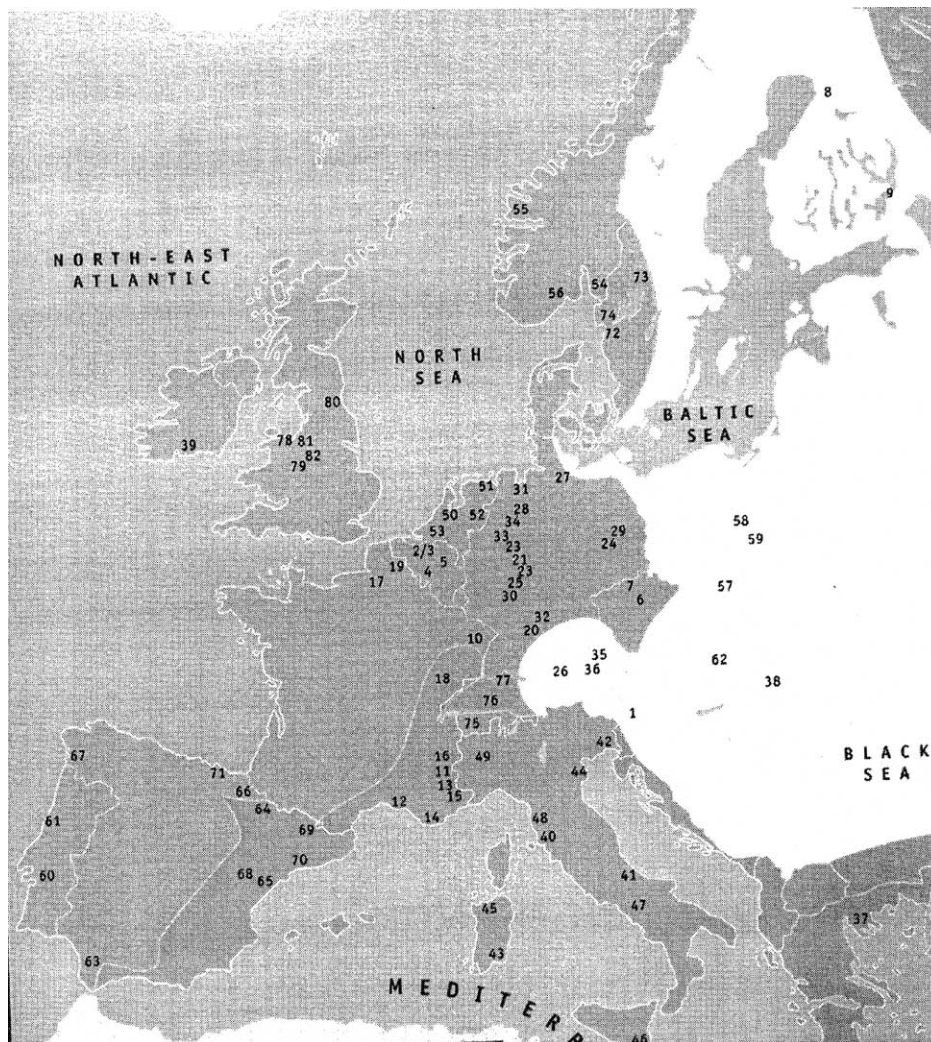


Fig. 4. Location of chlorine production plants in Europe (reproduced with permission; Euro Chlor, 2001).

has been the dominating process for the production of chlorine (Cl_2) and caustic soda in Europe, but can be produced also by the membrane cell and diaphragm cell process. Chlorine and caustic soda are produced in a fixed ratio (1:1.1) by chlor-alkali plants. Over the last two decades, membrane cell and diaphragm cell processes have replaced Hg cell technology in Europe, the US and Japan. The EUs Hg cell capacity is still about 64% of the total production capacity (Lindley, 1997), and there were still 45 Hg cell plants in operation in the EU in 2000 (Fig. 4 and Table 7). Between 1991 and 2000, average yearly Cl_2 production based on these three processes was about 9 Mt in western Europe (Euro Chlor, 1999, 2001; Lindley, 1997).

Table 7
Locations, company's names and capacities of mercury cell chlor-alkali plants in the European Union (Euro Chlor, 2001)

Country	Number on map	Company	Process	Capacity (kt)
Austria	–	–	–	–
Belgium	2	Solvay	Hg	100
Finland	8	Akzo Nobel	Hg	48
France	10	Albemarle	Hg	72
	13	Elf Atochem	Hg	170
	14	Elf Atochem	Hg, D	326
	15	Atochem	Hg	184
	17	Prod Chim d'Harbonnières	Hg	23
	18	Solvay	Hg, M	363
	19	Tessenderlo Chemie	Hg	18
Germany	20	BASF	Hg, D	360
	22	Bayer	Hg	240
	23	Bayer	Hg, M	220
	25	Vinnolit	Hg	150
	28	ECI	Hg	120
	30	Degussa	Hg	140
	31	Ineos Chlor	Hg	130
	32	LII Europe	Hg	150
	34	Vestolit	Hg	180
	35	Vinnolit	Hg	72
Greece	37	Hellenic Petroleum	Hg	37
Italy	40	Altair Chimica	Hg	27
	41	Ausimont/Montedison	Hg	70
	42	Caffarro	Hg	69
	44	Enichem	Hg	200
	45	Enichem	Hg	90
	46	Enchem	Hg	190
	47	Eredi Zarelli	Hg	6
	48	Solvay	Hg	120
	49	Tessenderlo Chemie	Hg	40
The Netherlands	52	Akzo Nobel	Hg	70
Portugal	61	Uniteca	Hg, M	61
Spain	63	EIASA	Hg	101
	64	EIASA	Hg	25
	65	EIASA	Hg, M	175
	66	Electroq. De Hernani	Hg	15
	67	Elnosa	Hg	33.5
	68	Erkima	Hg	150
	69	Quimical del Cinca	Hg	30
	70	Solvay	Hg	209
71	Solvay	Hg	63	
Sweden	72	Akzo Nobel	Hg	100
	74	Norsk Hydro	Hg	120
UK	79	Albion Chemicals	Hg	89
	81	Ineos Chlor	Hg, M	963
	82	Rohdia	Hg	29

Note: Hg: mercury; M: membrane; D: diaphragm.

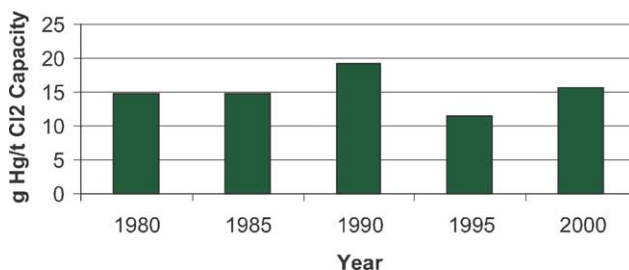


Fig. 5. Mercury in solid waste from chlor-alkali plants in western Europe (modified from Garny, 2001).

Due to process changes caused by strict regulations, atmospheric Hg emissions from chlor-alkali plants in western Europe has reduced from $3.3 \text{ g Hg t}^{-1} \text{ Cl}_2$ production 1989 to $1.24 \text{ g Hg t}^{-1} \text{ Cl}_2$ in 1997 (Euro Chlor, 1998). Based on 64% Cl_2 production by the Hg cell process and an emission factor 1.24 g Hg t^{-1} , atmospheric Hg emission from the chlor-alkali industry can be estimated 8.7 t in 2000, whereas in 1995 estimated Hg emission from caustic soda facilities summarised by the Working Group of Mercury (WGM) was 20.7 t (European Communities, 2001b).

At present, about 11.8 kt of Hg are in use in the Hg cells process for Cl_2 production in the EU-15 (Lindley, 1997). Waste from the Cl_2 industry contain Hg. It has been estimated that solid waste contain $10\text{--}17 \text{ g Hg t}^{-1} \text{ Cl}_2$ capacity. From this it can be estimated that in 1995 mercury waste was (EU-15 + Switzerland) 95.2 t based on a Cl_2 production capacity of 6.8 Mt and production of Hg containing solid waste corresponding to $14 \text{ g Hg t}^{-1} \text{ Cl}_2$ capacity (Garny, 2001). Fig. 5 indicates an average Hg content in waste per tonne Cl_2 capacity between 1980 and 2000.

The total phase out of Hg process for chlor-alkali production by the year 2010 was recommended by the Parties of the OSPAR Convention of the North European region (PARCOM Decision 90/3 of 14 June 1990). Among EU countries, discussions are going on regarding fate of 12 kt of Hg. If this Hg is considered as “hazardous waste”, there will be transport restriction beyond the national boarder due to “Basel Convention” (UNEP, 2002). European Commission (2002) suggested that this amount of Hg will not be governed by the Community Waste Legislation or by the Basel Convention. Each EU country has right to determine whether or not this Hg is a “hazardous waste”. Sweden has decided that Hg from chlorine industry is considered as “hazardous waste” and Swedish legislation prohibits movement of waste beyond the national boarder (UNEP, 2002). However, the European Chlorine Association (Euro Chlor) has recently signed an agreement with Miñas de Almadén, Mayasa (Spain) that the mining company will accept Hg from EU member countries under term that “it displaces ton for ton, Hg that would otherwise have been newly mined and smelted to satisfy legitimate uses” (UNEP, 2002).

However, it has not been defined what “legitimate uses” are. There is an evident risk that excess Hg from the European chlor-alkali plants will be used for gold mining by adding Hg to gold bearing river sediments, soils, and ores in developing countries. Mayasa has several offices situated outside Spain, most of which found in developing and gold mining countries, so the risk that Hg from Mayasa is abused in gold mining must be considered.

3.7. Sewage sludge

Sewage sludge is a residual product from industrial and urban wastewater. In recent years production of sewage sludge is increasing due to better effluent treatment methods and strict national regulation. In 1998, EU countries (except Italy) generated 7175 kt (dry matter) of sewage sludge of which the maximum amount (2660 kt) stemmed from Germany and the minimum amount (13 kt) from Luxembourg (EEA, 2002). The Hg concentration in sewage sludge is not given by each member country. Best on the data for 1996/1997 supplied by seven countries, it is observed that Hg concentration varies between 3 and 0.6 mg kg⁻¹ (dw). Table 4 indicates the Hg concentration in sewage sludge for individual country and the total amount of Hg locked in sewage sludge was 10.6 t in 1997. It is suitable for agricultural soils, but due to present of trace elements its use is restricted in most country. However, it is observed that the sludge is recycled, incinerated, landfilled, and occasionally delivered in the surface water by a few member countries. Fig. 6 indicates the amount of sewage sludge was used by different member states and 2.9 t of Hg entered the EU landfills through 1790 kt of sewage sludge (based on average Hg concentration: 1.62 mg kg⁻¹ dw).

4. Disposal methods

4.1. Overview

There is wide range of waste treatment methods which are generally based on thermal, physical, chemical or biological processes. The disposal methods for waste are generally: (a) landfills; (b) incineration; (c) composting; (d) recycling/recovery. Hg containing waste are not however, suitable for landfills, composting, and requires special treatment when incinerated (Fig. 6).

4.2. Landfills

Most EU countries have separate collection systems for waste. Still significant amount of Hg enters landfills or waste incinerators. Negative effects from Hg emitted as a consequence of this can only be reduced by exercising strict regulations, preferably at the production stage, and by educational/information measures. Disposal strategies vary from one country to another. Special landfills are generally constructed and maintained in accordance with the EU hazardous waste directive (EEA, 2001a). Such licensed landfills are in operation in the following states: Ireland <40%; United Kingdom, The Netherlands, Germany and France 40–70%; Denmark and Finland 70–90%; Austria, Belgium, Portugal and Sweden >90% (EEA, 1999a) Landfills, such as SAKAB in Sweden, Kommunekemi in Denmark and Ekokem in Finland, are equipped with the impermeable membranes and leachate collection systems needed to protect the ecosystem (Huse et al., 1999). Though the infra structures are expensive to build and demand considerable funds to be set aside for operation costs in the future to avoid that our waste becomes an economic burden of future generations. Hg in waste is generally pre-treated to obtain better stability before landfilling

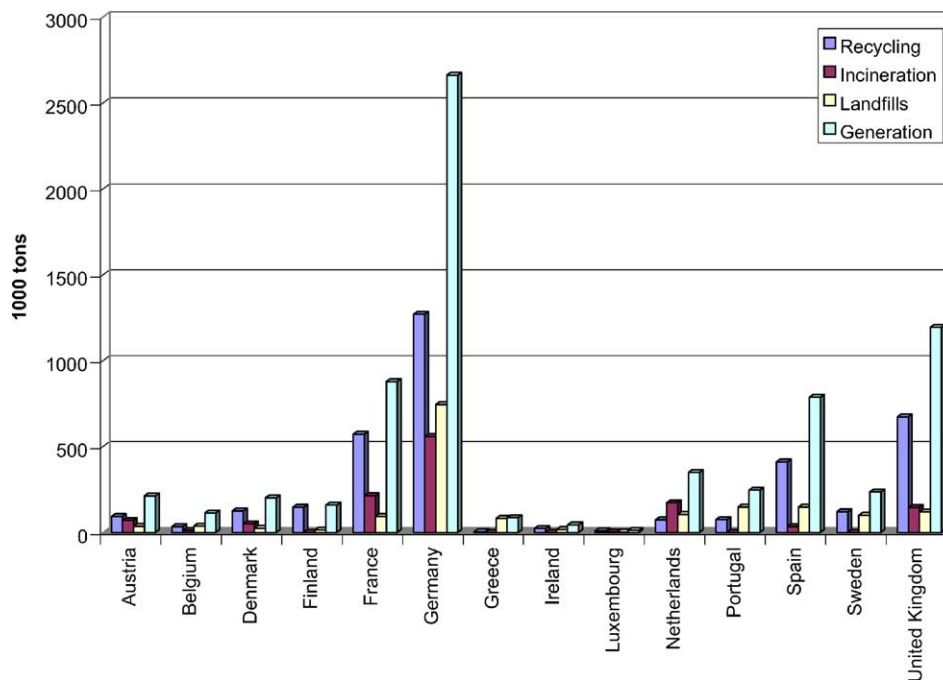


Fig. 6. Sewage sludge generation, recycling, incineration and landfill in the EU member states (except Italy; data for 2000) (modified after EEA, 2002).

and there is a limit value of Hg in waste. For example, in Sweden, this is $500 \text{ mg kg}^{-1} \text{ dw}$ (Huse et al., 1999). At landfilling of hazardous waste, there is pressures on the environment, in addition to leaching, also contribution to greenhouse gases by emissions of methane when the waste also contain organic materials, and land loss. The magnitude of the problems depends on the construction of the landfill, and the hydrological, geotechnical and topographical conditions (Colombo et al., 1996). However, it should be noted that modern landfills will always need economic resources for maintenance in the future. A flowchart for a landfill where environmental impacts from the landfill have been minimised is given in Fig. 7.

The Swedish Environmental Protection Agency (EPA) has developed a strategy for terminal storage of Hg in waste and surplus Hg. The concept is based on the conversion of Hg in waste in the elemental (Hg^0) or chemically stable form (e.g. HgS) and subsequently store it in a deep-rock storage facility. The groundwater will chemically favour this inert condition of the deposited Hg and the surrounding bedrock will protect the deposited waste for thousands of years or longer. This approach will guarantee that Hg in waste remain inside the border of a country and the risks that the Hg in the waste will be converted into Hg compounds that enter the environment practically eliminated (SOU, 2001; Swedish EPA, 1991; UNEP, 2002; US EPA, 2002).

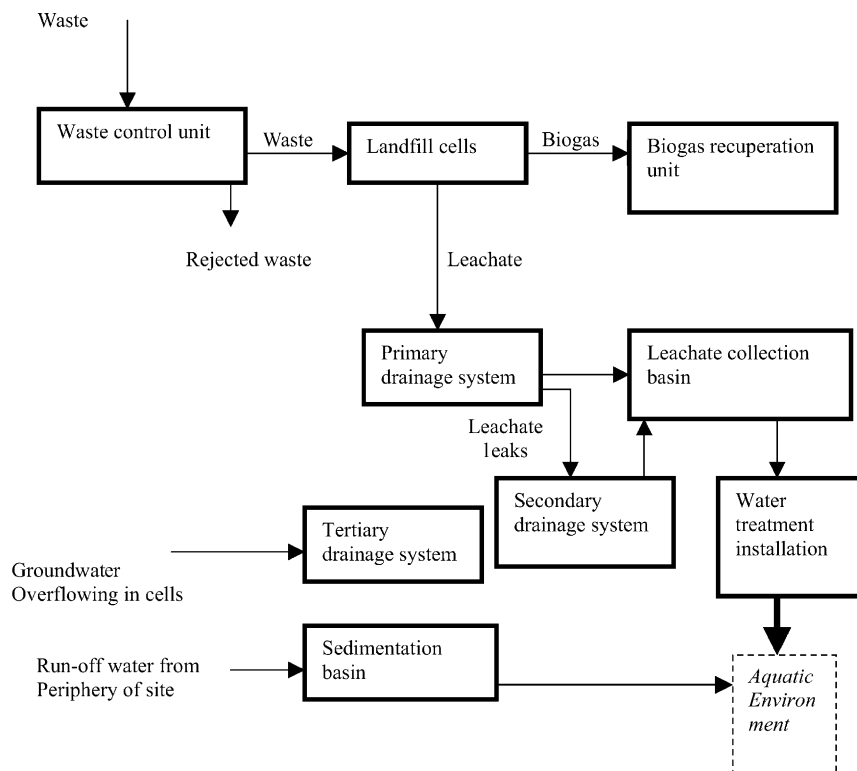


Fig. 7. Flowchart for a modern landfilling system (redrawn from Colombo et al., 1996).

4.3. Incineration

Hg in waste varies from one type of waste to another type. Hence its behaviours and release during incineration in three major groups of incinerators (municipal waste combustion (MWC), medical waste incinerator (MWI) and sewage sludge incinerator (SSI)) are difficult to generalise (European Communities, 2001b). In the EU-15 (except Portugal), there are 533 non-hazardous waste incineration plants of varying capacities, of which 280 are in France. In Finland, there is only one incineration plant for municipal waste. In addition to these, there are 239 incineration plants for hazardous waste in operation (EEA, 1999a). The main aim of incineration is to reduce the volume of municipal waste to be landfilled, and to destroy and detoxify the many hazardous organic components within the waste through oxidation. It is also an alternative source of energy which can be used for example for district heating (Hylander et al., 2003). In many countries emission control technologies for waste incinerators have been improved during the last decade due to which it is possible to reduce Hg emissions from the incinerators by 35–85% (Pirrone et al., 2001) or even above 95% (Hylander et al., 2003). It has been cited that incineration of household waste in the EU has caused 15–25% of atmospheric Hg emissions (Munthe et al., 2001; Umweltbundesamt/TNO, 1997). In the US, 90–94% Hg reduction was reported during com-

pliance tests at 115 large municipal waste incinerators equipped with control technologies (e.g. Fabric filter bag house, electrostatic precipitator, scrubber) (UNEP, 2002). Injection of activated carbon or nitrium sulphide to the flue gas prior to the electrostatic precipitator (ESP) or fabric filter (FF) is quite common in incineration of waste in EU countries, Canada and Japan (European Communities, 2001b). This method will remove 50–95% of Hg from the flue gas in MWCs (Nebel and White, 1991).

In the EU-15 states + 3 non-EU countries, 6–9 Mt of slag are produced from waste incineration processes. This product is mostly used for road construction, noise barriers, concrete production or landfilled. In Denmark and The Netherlands, 85–90% of slag are recycled, while only 50% is recycled in Germany, and in Sweden no slag is recycled (DEPA, 1998; International Ash Working Group, 1997). The slag unfortunately contains high concentrations of trace metals. Hg concentration varies from 0.02 to 7.75 mg kg⁻¹ (International Ash Working Group, 1997). Assuming 4 mg kg⁻¹, total Hg in slag from waste incinerators varies between 24 and 54 t. This material may contaminate the surrounding construction area if the surface is not sealed. Hg containing slag, residue or ashes must be in stable form for disposal if it cannot be used in a safe way.

4.4. Utility and non-utility boilers

It is important to note that the characteristics of coal, the combustion processes and the control equipment will influence Hg emissions to the atmosphere and its retention to residue and coal ash. Past studies indicated that retention of Hg from flue gas streams of the wet flue gas desulphurisation or dry FGD systems for utility boilers is different. In the former, retention percent varies between 30 and 50 whereas in the later it is 35–85%. But for the FF, the retention of particulate exceeds 99%. The durability of FF is quite limited (Pacyna and Pacyna, 2000). Hg in coal ash and residues have been discussed in Section 3.4.

4.5. Others

In any recycling of hazardous waste, costs, health risks, and possible environmental damages should be studied before starting this business and compared with costs for maintaining landfill sites for the future potential health risks and environmental damages from landfill sites. Recycling is higher up the “waste management hierarchy” than landfill disposal (ERM, 2000). If it is economically or environmentally³ viable, hazardous waste should be recycled, limiting the risk to environment and public health. Hg recovery units are mostly observed in the middle of the EU countries, e.g. Germany, France, The Netherlands, UK, and Ireland, and also in Nordic countries in Sweden and Finland. Hg from batteries, thermometers, instruments and lamps become hazardous to the ecosystem when they are not properly handled in accordance with regulations for hazardous waste. Human health is in danger when Hg is observed above certain level in our environment.

There are proven technologies for recovery of Hg from batteries, lamps, thermometers, and amalgam. These are based on distillation (wet/dry), thermal/chemical process, chemical precipitation, and solidifying.

³ The environmental benefit of recycling includes the benefit from less demand for mining activity.

4.5.1. Distillation process

It is used to recover Hg or to reduce the waste amount. Here the waste is placed in the vacuum chamber (temperature: 500–700 °C) where Hg is vaporised under sub-atmospheric pressure. The Hg vapour is passed into the cooling traps where Hg is condensed and collected in containers. The gas is passed to the atmosphere via carbon filter. The operation takes from 8 to 24 h and in one batch, 10,000 luminous tubes and 300–400 kg of button cells can be treated (TemaNord, 1999).

A German recycling company in Lübeck runs a vacuum thermal recycling plant for the processing of waste material containing Hg (batteries and cells) for recycling and disposal. Here the sorted Hg cells are processed in the vacuum thermal plant and the yearly recovery is about 100 t Hg (99.5%). Similarly, there are more than ten recycling companies in Germany engaged on the recovery of Hg and other raw materials from fluorescent tubes and other discharge lamps based on physical/dry; physical/wet and chemical/wet processes. In addition to the recovery of Hg, it is also possible to recover other components of the fluorescent tubes which can be re-used as raw materials (Genest, 1997). Generally, thermal or chemical reactions, and solidification are used to stabilise Hg to a form suitable compound (such as mercury selenide) for landfills. The process is developed by Elektronik and Återvinning AB, Göteborg Renhållningsverk and Tabulator AB in Sweden. But the Swedish Environmental Protection Agency has not approved to deposit the compound in waste landfills (TemaNord, 1999).

4.5.2. Chemical precipitation process

This process makes it possible to precipitate Hg in aqueous solution with sulphide compound, e.g. HgS. Hg from the crashed fluorescent tubes can be separated by the chemical precipitation process and the residue cake contains only 6 ppm Hg which satisfies the EPAs leaching test. The process is developed and used by Ekoteho Oy, Finland (TemaNord, 1999). In addition to chemical, there are biological processes by which Hg-bearing waste can be treated based on the use of micro-organisms, where degradation of organic compounds occurs. These processes partially or completely convert organic molecules into cellular mass, carbon dioxide, water and inorganic residue (Colombo et al., 1996).

5. Risk assessments

Risk can be expressed as the probability of an accident originating from inside or outside a process and its consequences. Risk assessment (RA) comprises information regarding the harmful effects of chemicals on humans and evaluation of the effects which can be used by the decision makers or by politicians. It generally includes: (i) risk identification, (ii) risk prediction and (iii) risk evaluation (Ellis, 1989; Swedish EPA, 1996). In the EU, there is no legislative guidance for Environment Impact Studies (EISs) However, society needs adequate information on the risks of substances and their adverse effects on man and the environment. There are hundreds of thousands of existing chemicals including metallic Hg and its compounds, and a couple of hundred new substances are introduced onto the market every year (Vermeire and van der Zandt, 1996), which may pose great threat to the environment. For this reasons risk assessment is necessary, although there is

lack of information available Hg cycles in the environment as a result of both natural and human activities. Its activities in the EU-15 cover 3191120 km² surface area. In this type of complex situation, it is rather difficult to make a correct comprehensive risk assessment of Hg in the EU countries. Euro Chlor (1999) recently has made investigation on risk assessment of Hg released from the Hg cell chlorine industry. In the case of terrestrial species, predicted environmental concentration (PEC) and predicted no effect concentration (PNEC) were calculated based on inorganic Hg species. The PEC/PNEC ratios for the terrestrial compartment was less than unity for soil organisms whereas the value is greater than unity for terrestrial predators. There are some uncertainties due to which the Euro Chlor member companies have decided on a further reduction of Hg emissions.

The following brief estimation indicates that substantial amounts of Hg enters landfills—a part of which is evaporated to the atmosphere, a part is leached to the groundwater and the rest is converted into methyl-Hg in the presence of organic waste:

- Total atmospheric emission of Hg in EU-15 in 1995: 112 t, whereas in Europe the estimated total emission of Hg: 342 t (Pacyna et al., 2000).
- Hg emissions from incineration of waste in EU-15: 7.2 t Pacyna et al. (2000) (no values have been cited for Ireland, Spain and Portugal, and the authors state the figures for other countries are in many cases lower than the real emissions).
- Hg collection efficiencies by different equipment at MSW combustion: 60%.
- Municipal waste entering into MSW combustors in the EU: 18% (EEA, 2003).

Based on the above information:

- Total Hg into municipal waste combustion in 1995:

$$\text{Mercury}_{\text{input to MWC}} = 7.2 / (1 - 0.60) = 18 \text{ t}$$

- Total mercury in municipal solid waste (MSW) would be:

$$\text{Mercury}_{\text{MSW}} = 18 / 0.17 = 106 \text{ t}$$

- Mercury from MSW enters into the landfill of the EU-15 states:

$$\text{Mercury}_{\text{Landfill}} = 106 - 18 = 88 \text{ t}$$

(Assuming that Hg in waste to landfill = Hg in waste to waste combustor and type and quality MSW to landfill = type and quality MSW to incinerator).

The above estimate would be higher if emission values from waste incinerators for Spain, Portugal and Ireland were known.

There are also risks from CCPs and recycling of waste: 16.5 t of Hg passes through CCPs which may leach or evaporate into the environment. In the past, many authors (Hylander, 2001a; Munthe et al., 2001; Rein and Hylander, 2000) have cited tonnes of Hg earlier used in society and then forgotten is moving and redistributed between water, soil and atmospheric compartments effecting impacts to the terrestrial and aquatic species. Although atmospheric Hg emissions in Europe have been reduced by 45% less from the beginning of the 1990s to 1995, the deposition rate in and around the industrial regions such as Europe, North America, and south-eastern China has increased by a factor of 2–10 during the last two

centuries due to transboundary deposition of Hg (Bergan and Rodhe, 1999). Still, in the studies of Pacyna et al. (2000), estimation accuracy for Hg data was 50% and emissions from incinerations have been underestimated due to limited information from European countries. In the EU-15, the Hg level in soil and sediments has increased (in Sweden by a factor of 4–7 in the southern and central area of Sweden and in the north by a factor 2–3) (Lindqvist et al., 1991). In many lakes of the northern regions of the EU, the Hg value in pike (*Esox lucius*) has exceeded $1 \mu\text{g Hg g}^{-1}$ wet weight (Louekari et al., 1994; Verta, 1990). Due to this increased concentration of Hg and other organic compounds in lake or marine fish, fishermen suffer, as they cannot sell their products to the market.

Ingestion of Hg through foods is generally the most important pathway exposing humans. The enjoyment of sport fishing and eating of fish disappears when the Hg content may affect one's health, for which the current EU limits for Hg in fish can be tightened for health reasons in individual countries (UNEP, 2002). In Sweden, half of 100,000 lakes contain high concentrations of Hg. Pregnant women are advised in Sweden not to eat freshwater fish (Pederby, 1995). Similarly, there are restrictions in the United States on consumption of fish ($\text{Hg} > 0.5 \mu\text{g g}^{-1}$ wet weight) in 32 states (Poulson, 1994).

Health problems of Hg and its compounds are not a new problem in the EU and EC. Council Regulation 793/93 on the evaluation and control of the risk of existing substances (CEC, 1993) was approved on 23 March 1993. Based on this regulation data collecting, risk assessment and proposal for risk management of the European Inventory of Existing Commercial Chemical Substances (EIECCS) are urgently required. Hence a multi-disciplinary investigation is necessary to find out the risk from the Hg in waste among the population in the EU-15 countries.

6. Discussions and conclusions

6.1. Trends

This study focused mainly on Hg in waste generated from different sources in the EU. Global Hg production has decreased from 5.6 kt in 1990 to 1.8 kt in 2000 (Hylander and Meili, 2003) whereas in the EU-15, virgin Hg production was reported at 680 t in 1999. The EU claims the largest Hg cell chlorine production, for which 631 t of Hg were acquired in 1996. The total mercury used in 45 Hg cell chlorine facilities in operation in the year 2000 was over 11 kt. Atmospheric Hg emissions have been reduced from chlorine production in the EU-15 member states, but there is only limited information on the fate of Hg in waste from the Hg cell chlorine facilities. In this study, the total Hg in waste from different sources was estimated to be about 990 t, including Hg from coal combustion products (16.5 t), landfills (88 t), chlor-alkali waste (95 t), waste incinerator slag (40 t) and data mentioned in Table 4.

Export and import of Hg-waste takes place amongst the EU and OECD countries. Generally, Hg-bearing waste is exported or imported for the recovery of Hg. Within the EU-15, Austria and Belgium exported the largest amounts of Hg in waste at the end of the 1990s. Euro Chlor and Mayasa have made an agreement on sending back excess Hg to Almadén (UNEP, 2002). Mayasa, in Spain, exports a considerable amount of Hg to developing

countries. Reselling transferred Hg on the world market will without doubt result in a flow of Hg to countries with less strict environmental protection than that of the EU and thus result in significant emissions to the environment, most evidently when Hg is used as an amalgamation agent in gold mining.

In recent years, special attention has been paid to Hg in thermometers, instruments, batteries, lamps, and amalgam. The use of Hg in amalgam is questioned worldwide (Skare and Enqvist (1994); Kauppi, 1996) and also Sweden, Finland, Denmark, Austria and Germany have recommended (non-binding legally) restrictions on Hg amalgams. There is a trend towards using less or no Hg in lamps, batteries and instruments.

6.2. Policies

A recommendation by the Parties of the OSPAR Convention of the North European region (PARCOM Decision 90/3 of 14 June 1990) has been forwarded for a total phase out of Hg process for chlor-alkali production by 2010; Maxson and Verberne (2000), however, believe that not all Hg cell facilities will be phased out before 2020. The problem may arise of how to store Hg from wastes, inside the borders of the EU.

The national economy of a country determines to a large extent the types of treatment or disposal methods are used to handle hazardous waste. Apart from incineration, Hg containing waste can be treated by chemical, physical and biological methods. Recovery or recycling Hg-waste operations should be guided by the policy-makers such that the process does not jeopardise human health or cause harm to the ecosystem. The EU-15 countries discourage disposal of hazardous waste by landfill, but the national policy of any of the particular countries may guide waste management policy.

The aims of the Basel Convention (UNEP, 2002) include: (a) to reduce transboundary movement of hazardous waste to a minimum, (b) to arrange disposal mechanisms near to the source of generation, and (c) to minimise the quantity of hazardous waste generated.

6.3. Future needs

Although attention has been paid to the management of hazardous waste in the EU, with special focus on Hg, Pb, Cd and As bearing waste, it is observed that many countries are unaware of the associated trends in Hg flows through products and waste. Except for Sweden, none of the EU member states publish data on Hg in waste from the mining sector, although many states practice mining of ores. The Luxembourg government has no information on the Hg flow associated with batteries, thermometers, lamps and amalgam. The information on Hg in waste from the member states of Finland, Denmark, Sweden and France is detailed to a reasonable level.

Efforts must be focused on developing appropriate treatment techniques and disposal of Hg in a safe way to avoid its transfer to other countries, where it will escape into the environment if used in gold mining, chlor-alkali facilities, thermometers and other uses. Due to its toxic effects in the environment, it is necessary to follow the material flow of Hg in the EU, and more reliable data are necessary (Table 4). The material flow information of any metal will be helpful to the decision makers of EU and other countries. Research is needed on health and environmental effects during Hg-waste management and handling.

It should be stressed that there is still a shortage of information due to which a complete inventory could not be made for this study.

Acknowledgements

This study was carried out in 2001 at the Department of Environmental Protection Science, University of Helsinki and the paper was accepted in the International Conference on Mercury as a Global Pollutant at Minamata, Japan, 15–19 October 2001. ABM has received partial information for mercury waste from the government authorities of 11 member states of the EU for this document. It is impossible to mention all names, but my sincere gratitude is expressed to Ms. Véronique Garny, Euro Chlor, Brussels, Ms. Claudia Olazábal, European Commission, Brussels, Ms. Nalini Basavaraja, UNEP, Switzerland, Mr. Magnus Nyström, Finnish Environment Institute, Helsinki, Ms. Natalia Glas, Federal Environment Agency, Vienna and many other organisations for supplying me with valuable information and documents on mercury waste in the EU. We are also grateful to the anonymous reviewers for their thoughtful comments. Finally, ABM acknowledges with thanks the assistance received in preparation of this manuscript from the staff members of the Department of Limnology and Environmental Protection, University of Helsinki.

References

- Anon. *Ecologistas en Acción*. Spain, August 10, 2000.
- Barregard L, Svalander C, Schütz A, Westberg G, Blohmé I, Mölne J, Attman P-O, Haglind P. Cadmium, mercury and lead in kidney cortex of the general Swedish population: a study of biopsies from living kidney donors. *Environ Health Perspect* 1999;107:867–71.
- Bergan T, Rodhe H. Mercury in the global troposphere: a three dimensional model study. In: Barbosa JR, Melamed R, Villas Bôas R, editors. *Proceedings of the Fifth International Conference on Mercury as a Global Pollutant*, 1999 May 23–27; Rio de Janeiro. p. 104.
- Berlin M. Mercury. In: Friberg L, Nordberg GF, Vouk VB, editors. *Handbook on the toxicology of metals*. Amsterdam: Elsevier, 1986. p. 387–435.
- Bjønstad SL, Linde MR. *Materialstrømanalyse av kvikksølv. Vurdering av alternativer, Utkast til SFT-rapport*, Oslo, Norway, 1994.
- Bergbäck B, Lohm U. Metals in society. In: Brune D, et al., editors. *The global environment—science technology and management*, vol. 16. Scandinavian Science Publisher/VCH Verlagsgesellschaft, Oslo/Weinheim, 1997. p. 276–89.
- Christiansen KM, Munck-Kampmann B. *Waste: annual topic update 1999*. Topic Report No. 2/2000. European Environment Agency, Copenhagen, 2000. 37 p.
- Colombo AG, Artola A, Gervast C, Haq G, Melaki I. An analysis of environmental impact studies of installations for treatment and disposal of toxic and dangerous waste in the EU. *Ispira study on projects under directive 85/337/EEC, Annex 1.9*. Joint Research Centre, European Commission, 1996. p. 200.
- CEC (Commission of the European Communities). *Council Regulation (EC) 793/93 of 23 March on the evaluation and control of the risks of existing substances*. *Off J Eur Commun* 1993:L84.
- DEPA (Danish Environmental Protection Agency). *Ecotoxicological assessment of sewage sludge in agricultural soil*. *Arbejdsrapport No. 69*, Copenhagen, Denmark, 1998.
- D'Itri FM. Minamata disease. In: Cunningham WP, Ball T, Cooper TH, Gorham E, Hepworth MT, Marcus AA, editors. *Environmental encyclopedia*. Gale Research, Detroit, MI, 1994. p. 521–2.
- D'Itri PA, D'Itri FM. *Mercury contamination: a human tragedy*. Wiley/Interscience, New York, 1977. 311 p.

- EEA. Environment in the European Union at the turn of the century. Environment Assessment Report No. 2, Copenhagen, 1999a. p. 111–31.
- EEA. Hazardous waste generation in EEA in selected European countries. Topic Report No. 14/1999. European Environment Agency, Copenhagen, 1999b. 94 p.
- EEA. Waste generation and management. Offprint from EEA 1999a. European Environment Agency, Copenhagen, 2001a.
- EEA. Hazardous waste generation in EEA member countries. Topic Report No. 14/2001. European Environment Agency, Copenhagen, 2001b.
- EEA. Review of selected waste streams. Technical Report No. 69, Copenhagen, 2002. p. 1–22. <http://www.eea.eu.int>.
- EEA. Kiev Report (Working title), 2003.
- EEA/UNEP. Chemicals in the European environment: low doses, high stakes? EEA and UNEP Annual Message 2 on the State of the Environment, Copenhagen, 1998. 32 p.
- Ellis D. Environments at risk: case histories of impact assessment. Berlin: Springer-Verlag, 1989. 329 p.
- EPA/Ireland (Environmental Protection Agency, Ireland). National hazardous waste management plan: summary', 1999. <http://www.epa.ie>.
- ERM (Environmental Resources Management). Part II of the study on implementation of decision IV/8—Annex VII issues. Prepared by the Environmental Resources Management to the Secretary of the Basel Convention, 2000. 11 pp. <http://www.basel.int>.
- Euro Chlor. Reduction of mercury emissions from the western European Chlor Alkali Industry. Emission #94/01, Brussels, Belgium, 1998.
- Euro Chlor. The mercury cell technology in western Europe. In: OSPAR Workshop on the Chlor Alkali Industry, 1999 September 27–29; Euro Chlor, Brussels, Belgium, 1999.
- Euro Chlor. Chlorine industry review: 2000–2001. Euro Chlor, Brussels, Belgium, 2001. 20 p.
- European Commission. Final report from the commission of the council concerning mercury from the Chlor-Alkali Industry. Commission of the European Communities, Brussels, September 6, 2002.
- European Communities. Decision No. 2001/0029/COD of the European Parliament and the Council Laying Down the Sixth Environment Action Programme, Brussels, April 30, 2002.
- European Communities. Ambient air pollution by mercury: position paper; prepared by the working group, Luxembourg, 2001b. <http://europa.eu.int>.
- European Communities. Regulation (EC) No. 2150/2002/EC of the European Parliament and the Council Laying Down the Sixth Environment Action Programme. Brussels, April 30, 2002.
- EUROSTAT. Waste generated in Europe, No. 83/99, 1999.
- Ferrara R. Mercury mines in Europe: assessment of emissions and environmental contamination. In: Ebinghaus R, Turner RR, de Lacerda D, Vasiliev O, editors. Mercury contaminated sites: characterization, risk assessment and remediation. Berlin: Springer-Verlag, 1999. p. 538.
- Genest W. Recycling of fluorescent tubes in Germany. Federal Environmental Agency, Berlin, Germany, 1997. p. 1–6.
- Genie Urbain-Genie Rural. Les déchets mercuriels en France. Mercury waste in France, Parts 1 and 2, Nos. 7-8:20-48 and 17-53, France, 1999. ISSN 0299-7258.
- Guimãraes JRD, Meili M, Hylander LD, Castro e Silva E, Roulet M, Mauro JBN, Lemos RMA. Mercury net methylation in five tropical flood plain regions of Brazil: high in the root zone of floating macrophyte mats but low in surface sediments and flooded soils. *Sci Total Environ* 2000;261(1–3):99–107.
- Harada M. Minamata disease: organic mercury poisoning caused by ingestion of contaminated fish. In: Jelliffe EFP, Jelliffe DB, editors. Adverse effects of foods. New York: Plenum Press, 1982. p. 134–48.
- Harada M. Minamata disease: methylmercury poisoning in Japan caused by environmental pollution. *CRC Crit Rev Toxicol* 1995;25:1–24.
- Heron H. Danish Environmental Protection Agency, June 2001 (cited by UNEP, 2002. 145 p).
- Hilliard HE. The materials flow of vanadium in the United States. United States Department of the Interior, Information Circular No. 9409, 1994. 20 p.
- Horvat M, Bloom NS, Liang L. Comparison of distillation with other current isolation methods for determination of methyl mercury compounds in low level environmental samples, Part II. *Water Anal Chim Acta* 1993;281: 153.

- Huse A, Lindmark GM, Sørensen PL, Weholt Ø, Mroueh U-M, Wahlström M. Investigation of categories and quantities of mercury waste, and treatment capacity in the Nordic countries. Tema Nord No. 546. Nordic Council of Ministers, Copenhagen, 1999. 90 p.
- Hylander LD. Global mercury pollution and its expected decrease after a mercury trade ban. *Water Air Soil Pollut* 2001a ;125(1–4):331–44.
- Hylander LD. Petition supported by 32 researchers on mercury to Environmental commissioner Margot Wallström, European commission, Brussels, Belgium, June 20, 2001 and Addressing the European Policy on Mercury, 2001b.
- Hylander LD, Meili M. 500 years of mercury production: global annual inventory by region until 2000 and associated emissions. *Sci Total Environ* 2003;304(1–3):137–44.
- Hylander LD, Sollenberg H, Westas H. A three stage system to remove mercury and dioxins in flue gases. *Sci Total Environ* 2003;304(1–3):13–27.
- International Ash Working Group. Municipal Solid Waste Incinerator Residues, Brussels, 1997.
- IPCS/WHO. Environmental health criteria, vol. 101: Methylmercury. Geneva: World Health Organisation, 1990.
- IPCS/WHO. Environmental health criteria, vol. 118: Inorganic mercury. World Health Organisation. Geneva; 1991.
- Ishihara N, Urushiyana K. Longitudinal study of workers exposed to mercury vapour at low concentration: time course of inorganic and organic mercury concentration in urine. *Toxicol Appl Pharmacol* 1994;155:161–8.
- Kauppi M. Current amalgam status and restrictions world-wide. *Heavy Met Bull* 1996;3(3). <http://vest.gu.se/~bosse/Mercury/Misc/HMB/amalgamrestrictions.html>.
- Lindley A. An economic and environmental analysis of the chlor-alkali production process. Prepared for the European Commission (DG III C-4, Chemicals, Plastics, Rubber). Brussels, Belgium, 1997. p. 64.
- Lindqvist O, Johansson K, Aastrup M, Andersson A, Bringmark L, Hovsenius G, Håkansson L, Iverfeldt Å, Meili M, Timm B. Mercury in the Swedish environment—recent research on causes. *Water Air Soil Pollut* 1991;55:1–251.
- Loebenstein JR. The materials flow of arsenic in the United States. United States Department of Interior, Bureau of Mines Information Circulation, IC 9382, 1994. p. 1–12.
- Louekari K, Mukherjee AB, Verta M. Changes in human dietary intake of mercury in polluted areas in Finland between 1967 and 1990. In: Watras CJ, Huckabee JW, editors. Mercury pollution, integration and synthesis. Lewis Publishers: CRC Press, 1994. p. 705–11.
- Maag J, Lassen C, Hansen E. Massestrømsanalyse for kviksølv (Substance flow assessment for mercury). Miljøprojekt nr. 344. Danish Environmental Protection Agency, Copenhagen, 1996 (in Danish with English summary).
- Maxson P, Verberne F. Mercury concerns in decommissioning chlor-alkali facilities in western Europe. ERM and Concorde East/West Sprl for The Netherlands Ministry of Environment VROM, The Hauge, September 2000.
- Maxson P, Vonkeman G. Heavy metals in products. Ministry of Housing, Spatial Planning and Environment, Directorate-General for Environmental Protection, The Hauge', Publikatierreeks Produktenbeleid nr. 1996/17.
- Meij R, Vredendregt L, Winkel H. The fate of mercury in coal-fired power plants. Presented in Air and Waste Management Association, Mega Symposium, August 21–23, 2001, Chicago, USA.
- Meijer PJ. Short survey of dangerous waste containing mercury in The Netherlands. Laboratory for Waste and Emissions, National Institute of Public Health and the Environment, Unpublished data, 2001.
- Mishima A. Bitter sea—the human cost of Minamata disease. Kosei Publishing, Tokyo, 1992. 231 p.
- Morrow H. Reducing cadmium risk in the US through an industry sponsored NiCd battery collection and recycling program. In: Proceedings of the OECD Workshop on Non-regulatory Initiatives, 1996 September 10–12; Crystal City, Virginia, USA. OECD Series on Risk Management No. 7, Paris, 1997. p. 25–32.
- Munthe J, Kindbom K, Kruqer O, Petersen G, Pacyna J, Iverfeldt Å. Emissions, deposition and atmospheric pathways of mercury in Sweden. *Water Air Soil Pollut* 2001. <http://www.kluweronline.com/issuetoc.htm/1567-7230+1+3/4+2001>.
- Nebel KL, White DM. A summary of mercury emissions and applicable control technologies for municipal waste combustors. Prepared for the US Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, September 1991.
- OECD. Environmental data compendium. Paris, 1997.
- Pacyna JM, Pacyna EG. Assessment of emissions/discharges of mercury reaching the arctic environment. The Norwegian Institute for Air Research, NILU Report No. OR 7/2000, Kjeller, Norway, 2000.

- Pacyna EG, Pacyna JM, Pirrone N. Atmospheric mercury emission in Europe from anthropogenic sources. *Atmos Environ* 2000;35:2987–96.
- Pederby H. Vår föda 1995;47(7) (in Swedish).
- Pirrone N, Munthe J, Barregård L, Ehrlich HC, Petersen G, Fernandez R, Hansen JC, Gran djean P, Horvat M, Steinnes E, Ahrens R, Pacyna JM, Borowiak A, Boffetta P, Wichmann-Fiebig M. EU ambient air pollution by mercury (Hg)—position paper. Office for Official Publications of the European Communities, 2001. <http://europa.eu.int/comm/environment/air/background.htm/mercury>.
- Poulson DUS. Unloading Toxic Mercury. *Booth/Newhouse Newspapers*, June 23, 1994.
- Rasmussen B. Kvicksølvholdige affaldsstrømme i Norde. Nordiske Seminar—og arbejdsrapporter, 1992. p. 572.
- Rein Kv, Hylander LD. Experiences from phasing out the use of mercury in Sweden. *Regional Environ Change J* 2000;1:126–34. <http://link.springer.de/link/service/journals/10113/bibs/0001003/00010126.htm>.
- Renberg I, Persson MW, Emteryd O. Pre-industrial atmospheric lead contamination detected in Swedish lake sediments'. *Nature* 1994;368:323–30.
- Sass BM, Salem MA, Smith LA. Mercury usage and alternatives in the electrical and electronic industries. US EPA Report, 1994.
- Scoullon M, von Kerman G, Thornton I. Towards an integrated EU policy for Heavy Metals. European Commission, DG Research, Brussels, 2000. p. 537.
- SFS (Swedish Code of Status) 1991:98. Ordinance on export and import of hazardous waste, Stockholm, 1991 (in Swedish). <http://www.reqeringen.se>.
- Skare I, Enqvist A. Human exposure to mercury and silver released from dental amalgam restorations. *Arch Environ Health* 1994;49(5):384–94.
- Soares MCC, Mello L. The International Mercury Market and Mercury Consumption in Brazil, Brazilian Institute of Economic and Social Analysis, IBASE', Rio de Janeiro, Brazil, 1994. 20 p.
- SOU. Kvicksilver I säkert förvar (A safe mercury repository). Swedish Government Official Reports Series No. 2001:58, Stockholm, Sweden, 118 p. <http://www.naturvardsverket.se>.
- Steurer A. Material flow accounting and analysis, Stockholm, Sweden: Statistics Sweden, May 1996.
- Svensk författningssamling. Swedish code of statutes 1991:1290. Ordinance on certain mercury-containing products. Fakta Info Direkt, Stockholm (in Swedish).
- Swedish EPA. Terminal storage of mercury: an important step on the road to a sustainable society (summary). Swedish Environmental Protection Agency, Stockholm, 1991. p. 12. ISBN 91-620-9856-x.
- Swedish EPA. Risk assessment—health—environment. Swedish Environmental Protection Agency, Stockholm, 1996. p. 52.
- Sznopek JL, Goonan TG. The material flow of mercury in the economies of the United States and the World'. US Geological Survey Circular No. 1197, 2000. 28 p. <http://greenwood.cr.usgs.gov/circulars/c1197/>.
- TemaNord. Joint nordic strategy for treatment of mercury waste: investigation of categories and quantities of mercury waste, and treatment capacity in the Nordic Countries. TemaNord No. 546, Copenhagen, 1999. 90 p.
- Umweltbundesamt/TNO. The atmospheric emission inventory of heavy metals and persistent organic pollutants for 1990. Berlin, Germany, 1997.
- UNEP (United Nations Environmental Programme). Global mercury assessment. United Nations Environmental Programme, Geneva, Switzerland, 2002. p. 117–2.
- USDoE (United States Department of Energy). US Department of Energy, International Energy Outlook 1998. EIA 0484(98):114.
- US EPA (United States Environmental Protection Agency). Control of mercury emissions from coal fired electric utility boilers. Interim Report Including Errata, March 21, 2002. EPA-600/R-01-109, National Risk Management Research Laboratory, Research Triangle Park, NC, April 2002. <http://www.epa.gov/appcdwww/aptb/EPA-600-R-01-109corrected.pdf>.
- USGS (United States Geological Survey). US Geological Survey. Mineral Commodity Summaries, 1999.
- van Beusekom C. Hazardous waste in the European Union. In: Statistics in focus: environment and energy. Eurostat, Luxembourg, 1999. p. 8.
- Vermeire T, van der Zandt P. Procedures of hazard and risk assessment. In: van Leeuwen CJ, Hermens JLM, editors. Risk assessment of chemicals: an introduction. London: Kluwer Academic Publishers, 1996. p. 293–337.

- Verta M. Mercury in Finnish forest lakes and reservoirs: anthropogenic contribution to the load and accumulation in fish. Doctoral Dissertation. University of Helsinki. Publication of the Water and Environmental Research Institute, National Board of Waters and the Environment, Finland, 1990. p. 6
- vom Berg W, Feuerborn H-J, Puch K-H. Production and utilisation of coal combustion products (CCPs) in Europe. ECOBA European Association for use of the by-products of coal-fired power stations eV. Essen, Germany, Unpublished report, 2001.
- Watras CJ, Huckabee JW, editors. Mercury pollution: integration and synthesis. Boca Raton: Lewis Publishers, 1994. 727 p.