Life-cycle flow of mercury and recycling scenario of fluorescent lamps in Japan

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ARTICLE INFO ABSTRACT

We summarized the mercury flow of mercury-containing products from their manufacture to their disposal in Japan and discussed the current management of mercury-containing hazardous household waste (HHW). The mercury flow originating from these products was estimated to be about 10–20 tonnes annually, about 5 tonnes of which was attributable to fluorescent lamps, the major mercury-containing product in Japan. The recent rapid increase in digital home electronics with liquid crystal displays (e.g., televisions, personal computers, mobile phones, and digital cameras) has led to a marked increase in the production of backlights, which are also fluorescent and contain mercury. Most of the annual flow was disposed of as waste, with only 0.6 tonnes Hg recovered. The mercury flow for end-of-life fluorescent lamps (excluding backlights) was analyzed under three scenarios for Kyoto, Japan for 2003: the present condition scenario, the improved recycling scenario, and the complete recycling scenario. Under the present condition scenario, mercury flow was calculated to be 34 kg Hg for incineration, 21 kg Hg for landfill, and only 4 kg Hg for recycling. The complete recycling scenario shows a simple flow, with all mercury recycled. Under this scenario for Kyoto, we calculated that a cyclic system having 47 kg of mercury (3.5 tonnes Hg in Japan) could be established if all fluorescent lamps (excluding those stored in residences) were collected and recycled. Mercury is a HHW priority chemical, and we need to limit its use and establish a closed-loop system. There are currently no regulations to achieve this, and the management of most HHWs is left to local governments. Therefore, products are disposed of in landfills or incinerated, except for some that are voluntarily collected and recycled. In order to recycle all of the waste fluorescent lamps, we must have a complete recycling system that has a high rate of public participation in collection. We also must have a closed-loop system of mercury recovery and reuse in which all stakeholders participate. Furthermore, it is important to share information and policies regarding fluorescent lamp recycling and related technologies with other countries, especially those in other countries, where fluorescent lamps are becoming more popular because of their high energy efficiency and long life. Also, it is important to develop mercury free and energy efficient lamps including LEDs (light emitting diodes).

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1. Introduction

To prevent and control global mercury pollution, it is necessary to keep an emission inventory and assess the flow of mercury in each country of the world (UNEP Chemicals, 2002). Coal combustion is the major source of mercury emissions in Asia (UNEP Chemicals, 2002). However, the technology to reduce the burden from coal combustion has been installed in Japan (Kida and Sakai, 2005). Management of mercury contained in consumer products will be the next important step for controlling mercury emissions in Japan. Mercury is used in a number of household products, including fluorescent lamps and thermometers. Industry efforts to reduce the amount of mercury used have not yet been entirely successful for many products. In terms of hazardous household waste (HHW), recycling systems operating on a commercial scale have been developed for only a limited number of products, such as televisions, air conditioners, refrigerators, and washing machines. As a result, most mercury-containing products, including fluorescent lamps, are expected to be disposed of in landfills or incinerated.

Substance flow analysis, which deals with the analysis of flows and stocks of specific substances for given areas and time periods (Guinee et al., 1999), has been used to address policy issues and management of key substances from the point of view of environmental risk or hazard. Within this framework, a number of models and methods have been studied. Van den Voet et al. (1994) developed models that describe substance flow both in the economic system and in the natural environment (Bouman et al., 2000). Handbooks and manuals have also been published, and there have been many case studies for various substances such as trace elements (Cd, Hg, Ni, Cr, Zn, Pb, etc.), chlorine and its compounds (HCl and polyvinyl chloride, etc.), and persistent organic pollutants (polychlorinated biphenyl ether, brominated flame retardants, etc.) (Van der Voet et al., 1994; Bouman, 2000; Brunner et al., 2003; Rydh et al., 2003; Lindqvist and von Malmborg, 2004; Matsuto et al., 2004; Murakami et al., 2004; Kabata-Pendias, 2004; Kabata-Pendias et al., 2007).

Some studies of mercury have focused on local areas or facilities. Others have looked at decision making in waste and resource management. Rechberger and Brunner (2002) used an approach based on a comprehensive material flow analysis and Shannon's statistical entropy function and found evidence of the potential for modern incinerators to control the flow of materials, including mercury. Ayres and Ayres (2000) focused on mercury from a combined Material Flow Analysis/Life Cycle Assessment (MFA/LCA) perspective. Christensen et al. (2004) analyzed mercury balance for Denmark in 2001 and estimated that the consumption of mercury was between 2.1 and 5 tonnes/year. The greatest intentional use of mercury was in the mercury amalgam used in dental fillings, which made up about one-third of the total consumption and 70% to 80% of the intentional consumption. Material flow analysis of mercury in the United States for 1989 and 1990 showed that the manufacturing, use, and disposal of products containing mercury accounted for the release of about 1000 tonnes/year and that the amount recovered was about 150 tonnes/year (Jasinski, 1995). Mercury released to the air and water from products was reported to be drastically reduced in the year 2000 in the US (Barr Engineering Company, 2001). Assessment of atmospheric mercury emissions in Finland (Mukherjee et al., 2000) showed that the total emission of mercury had been decreased from 1,140 kg in 1990 to 620 kg in 1997, and that the 45% emission reduction was due to emission reduction of improved gas cleaning equipments and processes in coal-fired power plants and strict pollution control laws. Mukherjee and Zevenhoven (2006) discussed mercury in coal ash and its fate in the Indian subcontinent, and suggested that it was a big task to generate low cost energy while protecting the ecosystem by minimizing the production of ash and also increasing its utilization. Global flow and historical emissions have also been discussed by Hylander and Meili (2003, 2005). They showed the rise and fall of mercury in quantity and cost through 500 years of production and consumption. They reported that the chlor-alkali industry dominated global mercury consumption, and noted that political guidance was necessary to ensure that large stocks of mercury in industrialized countries were appropriately decommissioned. Modern cycling of mercury and its behavior and fate in the environment for the last three decades in relation to global scale information is lacking (Lindberg et al., 2007).

In this paper, we first analyze and summarize the flow of mercury from the manufacture of mercury-containing products to their disposal in Japan. Then, we describe the current management of mercury-containing HHWs and discuss how to control them.

2. Methods

2.1. Substance flow analysis for mercury-containing products

Focusing on products containing mercury in Japan, we analyzed the annual life-cycle flow and stock of mercury between 2000 and 2003 (Asari et al., 2005). In this analysis, except for recovery from past domestic products including fluorescent lamps, batteries and other collection and from contaminated soil, we did not include mercury in polluted soil, sludge, stocks at landfills or other sites which weren't recovered, emissions from production processes, impurities in raw materials (e.g., fossil fuels), and natural sources.

The life cycle of products was divided into four stages: material, products, end-of-life products, and incineration. Factors of input, output, and stock for the main products at each stage were estimated on the basis of available data or assumptions. For end-of-life products, excluding the mercury behavior related the incineration emission, only collection and handling amounts in recycling and landfills were described.

Most data were obtained from public statistics by using a data research system or the internet as described below. We also performed interviews to double check the accuracy and reliability of our data. Even so, further verification and refinement of flow and emission values would be desirable in future research.

Material stage and import and export amounts were obtained from the Trade Statistics of Japan (Ministry of Finance, 2005). Domestic supply (only from stock and recovery because
appliances, and others, the Iron and Steel, Non-ferrous Metal and Fabricated Metals Statistics of Japan (Ministry of Economy, Trade and Industry, 2005a,b). We used reported values obtained from the predominant recycling company for recovery amounts (Nomura Kohsan Co., Ltd., 2005).

For the products stage, public statistics were our main source, except for estimations of some factors concerning fluorescent lamps and batteries, which are described below. Backlights are fluorescent lamps used in liquid crystal displays for digital home electronics. The flow and stock of backlights that accompany televisions (TVs), personal computer (PC) monitors, and other liquid crystal displays used at home, offices and in industries were also targeted. For domestic production and sale of fluorescent lamps, excluding backlights, backlight products (monitors), and battery materials (for silver oxide batteries), the Indices of Industrial Production of Japan (Ministry of Economy, Trade and Industry, 2005a,b), for foreign production and sale of fluorescent lamps, excluding backlights, backlight products (TVs, PCs, and monitors), and battery materials (for all products), Trade Statistics of Japan (Ministry of Finance, 2005), and for domestic sale of backlight products (TVs and PCs), data from the Japan Electronics and Information Technology Industries Association (JEITA, 2005) was used. For domestic production and sale, foreign production and sale, and storage of amalgam, inorganic chemicals (Mercurochrome), and measurement devices (thermometers and sphygmomanometers), data were obtained from the Indices of Medical Industrial Production of Japan (Ministry of Health, Labour and Welfare, 2005). Then, for the domestic production and sale of inorganic chemicals (others), electric domestic demand, and stock amounts were obtained from the Iron and Steel, Non-ferrous Metal and Fabricated Metals Statistics of Japan (Ministry of Economy, Trade and Industry, 2005a,b). We used reported values obtained from the predominant recycling company for recovery amounts (Nomura Kohsan Co., Ltd., 2005).

The numbers of fluorescent lamps and batteries were estimated in the following manner. The number of each product produced in year t was calculated as shown in next equations by using the rate x, which represents the ratio of the imports that were directly sold through companies without being reported to the Indices of Industrial Production of Japan (Ministry of Economy, Trade and Industry) to the total imports reported in the Trade Statistics of Japan (Ministry of Finance) (estimation A). We also made a second estimation under the assumption of stock for those products for which only production data were available (estimation B). Total production for a given product was then multiplied by mercury content per product. Parameters and sources are shown in Table 1. Definitions and calculations are as follows:

\[
\begin{align*}
\text{Domestic production in year } t & \rightarrow P_t = \frac{x}{100} D_0 \\
\text{Domestic sales in year } t & \rightarrow S_t = \frac{x}{100} D_0 \\
\text{where,} & \\
D_0 & \text{is production in year } t \text{ reported in the Indices of Industrial Production of Japan} \\
S_0 & \text{is sales in year } t \text{ reported in the Indices of Industrial Production of Japan} \\
E_0 & \text{is stock in year } t \text{ reported in the Indices of Industrial Production of Japan}
\end{align*}
\]

<table>
<thead>
<tr>
<th>Products</th>
<th>Estimations for flow of products</th>
<th>Collections for recycling [R]</th>
<th>Additional stocks [ST]</th>
<th>Disposal (% of total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescent lamps excluding BLs</td>
<td>50%</td>
<td>10^b</td>
<td>196-276 kg Hg^c</td>
<td>4.5% of [E-R]</td>
</tr>
<tr>
<td>BLs in TVs and PCs</td>
<td>70%</td>
<td>150^f</td>
<td></td>
<td>100%^x</td>
</tr>
<tr>
<td>BLs in monitors</td>
<td>90%</td>
<td>50^f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BLs in others</td>
<td>90%</td>
<td>60^f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amalgam</td>
<td></td>
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<td></td>
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<tr>
<td>Resinants</td>
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<tr>
<td>Electric appliances</td>
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<tr>
<td>Thermometers</td>
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<tr>
<td>Other instruments</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkaline button battery</td>
<td>50%</td>
<td>1.5^i</td>
<td>297-374 kg Hg^c</td>
<td>19% of [E-R]</td>
</tr>
<tr>
<td>Silver oxide battery</td>
<td>50%</td>
<td>1^i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc-air battery</td>
<td>50%</td>
<td>0.5^i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mercury oxide battery</td>
<td>100%</td>
<td>620^h</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BLs: Backlights.
^a See text for explanation of x.
^b Mercury content for each lamp (Oshima, 2004).
^d From: questionnaire survey in Asari et al. (2005).
^e Average ratio for all waste in Japan.
^f Estimated from the mercury content of each lamp (Oshima, 2004) and the number of lamps for each product (from our research on end-of-life products).
^g Assumed not yet to be disposed of.
^h Murata (1983).
^i Personal communication data from the Battery Association of Japan.
I is imports in year t reported in the Trade Statistics of Japan
E is exports in year t reported in the Trade Statistics of Japan

For the domestic end-of-life products stage (W), as shown in Table 1, available data for collections for recycling (R) and additional stocks at home (H) were introduced, and disposal (D) was calculated as follows:

\[
D = W + R + H
\]

Many studies have examined the rates of mercury removal by various incinerator flue-gas treatments (Takaoka, 2005a). In Japan, technologies developed to reduce dioxin emissions (bag filter and activated carbon adsorption) have been installed in many waste treatment facilities, and these seem to have had a remarkable effect on the rate of mercury removal. The rate of mercury removal has increased to 97% after this reform, up from the previous 22% (Kida et al., 2004). Mercury and mercury compounds are now priority pollutants in Japan under the Air Pollution Control Law, and their environmental presence is now monitored. In our flow analysis, the ultimate destination of mercury during incineration was considered in extra detail. Emissions were estimated under two flue-gas treatment scenarios (a maximum removal of 90%, assuming a bag filter plus activated carbon adsorption, and a minimum removal of 22%, assuming an electrostatic precipitator). Two ranges are given for the distributions of mercury in the gas, ash, or others (water) emitted from incinerators.

2.2. Scenario analysis for end-of-life fluorescent lamps

Three scenarios were used to analyze the mercury flow of end-of-life fluorescent lamps, excluding backlights. Data from 2003 for Kyoto, a city of 620,000 households (1.3% of all households in Japan), were analyzed under a “present condition scenario”. Results were also calculated for an “improved recycling scenario” and a “complete recycling scenario” to determine the effects of the circulation system. In the improved recycling scenario, recycling for collected lamps is assumed to improve through the activation of collecting bodies or recycling industries. The disposal behavior of consumers is assumed not to change. The complete recycling scenario adds the assumption of changing consumer behavior to the improved recycling scenario.

The number of waste fluorescent lamps was determined using three factors: (1) the results from a substance flow analysis of mercury, (2) the amount of sales of fluorescent lamps in Kyoto as calculated by using the ratio of households in Japan and Kyoto reported in statistical data (the Ministry of Internal Affairs and Communications, 2005) for residential use, and (3) the ratio of commercial and industrial offices in Japan and Kyoto (Asahi News Paper, 2004a). The amount of waste was assumed to be equal to sales.

The primary routes of disposal from households are: (i) storage, end-of-life lamps left at home; ii) collection by local government as municipal solid waste (MSW), can and bottle, and bulky waste; iii) collection by sales shops; and iv) collection by a moving company. The distribution of the disposal routes was determined on the basis of results from questionnaire survey (Asari et al., 2005) for the present condition scenario. For the improved recycling scenario, the disposal route was same as the present condition scenario, however 50% of lamps disposed of as MSW are assumed to go to collection and recycling by local government. In the complete recycling scenario, collection and recycling systems are assumed to be established, as is consumer participation. In the present condition scenario, 50% of lamps collected by sales shops are assumed to be recycled and the other 50% is treated as industrial waste, and 100% of lamps collected by a moving company are treated as industrial waste. In both the improved recycling and the complete recycling scenarios, a 100% recycling rate is assumed from these sources.

3. Results and discussion

3.1. Mercury flow originating from products

3.1.1. Substance flow for mercury-containing products

Fig. 1 shows the estimated flow of mercury originating from products in Japan during 2000–2003. As shown in the figure, mercury at the raw materials stage is estimated to be 105–168 tonnes/year, which is one order of magnitude higher than that at the product stage (14–21 tonnes/year). Storage and export related to recovery from various sources have a larger amount of mercury flow than domestic production. This analysis also showed that most mercury-containing products were disposed of as waste; only 0.6 tonnes, or 4% of the total amount of mercury waste, was recovered. The amount of mercury used in all types of fluorescent lamps was calculated to be 4.8–6.7 tonnes/year, which makes up 28% to 46% of the total mercury contained in products sold domestically.

3.1.2. Materials

Most of the mercury raw material originates from domestic supplies and domestic storage (Fig. 1). The amount of mercury imported into Japan has ranged 5–45 tonnes/year during 1990–2003, and the amount was higher in the early 1990s (Fig. 2). The amount of mercury exported averages about 5 tonnes/year, although there have been irregular peaks every few years, such as 126 tonnes/year in 2003 (Fig. 2). It is possible that this exported mercury is used in a third country because countries importing from Japan include the United States and the Netherlands, which are themselves international exporters.
of mercury. Considering the global movement towards discouraging the use of mercury in order to prevent its release into the environment and to prevent human exposure, it is important to keep track of this exported mercury, which exceeds the domestic supply every few years.

3.1.3. Products

Mercury has been used for various purposes, including household products [The Chemical Daily, 2002]. Some of those uses (e.g., in sodium hydroxide production, pesticides, and dry-cell batteries, and as a catalyst for acetaldehyde production) have now been discontinued in Japan (Uemura et al., 2002). Efforts to find alternatives to mercury and to reduce its use especially for batteries, instruments (thermometer and sphygmomanometers), inorganic drugs and dental amalgam have resulted in significant reductions in demand in recent years (Fig. 3); however, because of increased use in the categories of "fluorescent lamps" and "others", the demand increased slightly for 2003.

3.1.3.1. Fluorescent lamps. A small amount of mercury is essential in fluorescent lamps, which are energy efficient and widely used for domestic lighting, offices and industries. Efforts to reduce the amount of mercury used in each lamp...
have been successful. The amount of mercury per lamp decreased from 50 mg in 1984 to 10 mg in 2002. Also, mercury free and energy efficient light technology is coming such as LEDs (light emitting diodes) and field emission lamps. On the other hand, despite efforts to develop a replacement technology, nothing seems to be superior to mercury in terms of efficiency and economy (Oshima, 2004).

More mercury was used for fluorescent lamps than for any other type of product in 2003, accounting for approximately 40% of the total use of mercury. The recent rapid increase in digital home electronics with liquid crystal displays (e.g., TVs, PCs, mobile phones, and digital cameras) has led to a marked increase in the production of backlights (Fig. 4).

### 3.1.5. Management of mercury-containing waste

Special handling is required for mercury-containing industrial waste because it is designated as a “specially controlled industrial waste" in Japan. There currently are, however, no such regulations for mercury-containing HHW, and the management of most HHW is left to each local government. Therefore, products are disposed of in landfills or incinerated, except for some that are voluntarily collected and recycled.

There seems to be large differences between Japanese cities in the handling of mercury-containing domestic waste, especially in the management of fluorescent lamps and thermometers. Fluorescent lamps are often collected separately to prevent accidents during collection and transportation, but they are not necessarily recycled after collection.

The estimated number of recovered fluorescent lamps and their recovery rates are shown in Fig. 5. The collection rate...
these products must be considered because a considerable increase in this type of waste is foreseen in the near future.

3.2. Scenario analysis for end-of-life fluorescent lamps

3.2.1. Three scenarios for end-of-life fluorescent lamps

Results of the scenario analyses are shown in Fig. 6.

In the present condition scenario (Fig. 6A), mercury flow is calculated to be 34 kg Hg for incineration, 17 kg Hg for...
crushing, 21 kg Hg for landfill, and only 4 kg Hg for recycling. Incinerated and land-filled mercury from end-of-life fluorescent lamps contributes to residential waste, and crushed lamps contribute to commercial and industrial waste.

In the improved recycling scenario (Fig. 6B), mercury flow for crushing, incineration, and landfill is almost half of that in the present condition scenario. This suggests that the mercury burden could be reduced drastically by recycling materials that can be collected now. This is especially true for residential recycling.

The complete recycling scenario (Fig. 6C) shows that a cyclic system with a total of 47 kg of mercury in Kyoto (3.5 tonnes Hg in Japan) can be established when all fluorescent lamps, excluding those stored in residences, are collected and recycled.

### 3.2.2. Management of mercury-containing waste

Only 4% of the total waste mercury originating from products is now recycled in Japan; most is disposed of in landfills or emitted to the environment. Emission to the environment is also likely to increase because a part of mercury recycled is being exported.

Nowadays, systems for managing HHWs should be based on the notion of hazardous household chemicals (HHCs) (Asari et al., 2005). The use and management of materials over the entire life cycle must be assessed in the context of the regional and global pollution problem. Improving the collection rate alone is not sufficient for properly handling HHWs. Recovery and detoxification standards are needed, as are legalistic rates for each HHC. Mercury is a priority HHC that must be tackled by regulators, and fluorescent lamps, thermometers, and batteries are the main target products. Considering global mercury pollution, the first task is to avoid its use as much as possible. Because mercury free thermometers are common, voluntary restriction or regulation in the market is required.

For products for which alternatives are not available, we must limit their use and establish a closed-loop system. In Japan, fluorescent lamps are the main target products, and they can be used as a model on which to build a closed-loop system. In establishing such a system, it is important to control risks during recycling. Of course, recycling methods that place a low burden on the environment and human health are required. Moreover, we need to develop technologies and systems to bring about cyclic uses of mercury within the closed system, so that the recovered mercury will not be a potential source of pollution. Solving technical and regulatory problems is necessary, but the active participation of citizens will also be an important factor. In particular, some kind of regulation, incentives, or creation of new business models must be considered to ensure a high rate of public participation in the collection of used fluorescent lamps. In the European Union, we can see some examples: Austria has a collection rate of more than 50% that is aided by a deposit system for recycling (1 euro for 1 unit); Germany, with the world's largest fluorescent lamp collection infrastructure (220 collection points, a collection rate of 70% to 80%, and 20 recycling plants), has a recycling rate of almost 100% (EC, 2002). In Japan, Matsushita Electric Industrial Co. (Panasonic, 2005) sells "lighting to companies, but the lamps themselves remain the property of Panasonic to be recycled by Panasonic. We need to study the performance of these models and clearly present a framework on which to build essential technologies and systems. The demand for fluorescent lamps is increasing with new usages such as backlights. Except for backlights installed in PCs, there is no established recycling route for these materials. As an example, the Law for the Recycling of Household Appliances does not apply to liquid crystal TVs, and in many localities, they are classified simply as bulky waste. Appropriate responses to such new uses are required.
5. Conclusions

The substance flow of mercury in Japan was summarized for mercury-containing products, and the current management of these products as HHWs was described and the problems considered. Our main findings can be summarized as follows:

- The amount of mercury flow originating from products was estimated to be about 10–20 tonnes annually, 3 tonnes of which was from fluorescent lamps. The use of fluorescent lamps for backlights is increasing, and most fluorescent lamps were disposed of as waste. Only 0.6 tonnes of mercury, about 4% of the total, is recovered annually.

- Only some types of products are currently controlled as HHWs. It is necessary to consider target products and management policies by using the notion of HHC. Mercury is a priority chemical, and we need to limit its use and establish a closed-loop circulation system for uses where Hg cannot be replaced.

- Fluorescent lamps are a major mercury-containing product in Japan, and they can be used as the model on which to build a closed-loop system. We need to develop technologies and systems to bring about multiple uses of mercury in the closed system so that recovered mercury will not be a potential source of pollution, whether domestically or abroad.

It is necessary to create a thorough recycling system that has (1) a high rate of public participation, (2) a closed-loop system of mercury recovery and reuse, and (3) the participation of all stakeholders. Therefore, in addition to discussing how to publicize the program so as to encourage participation or collection systems, it is also desirable to consider the creation of certain regulatory measures, new technologies for alternatives to mercury use, and new recycling business models. Considering recent global economic activities, it is also important to share information and policies about HHW management and treatment technologies with other countries, especially those in mainland Asia where the market of fluorescent lamps will possibly be expanded in the near feature.

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