火葬あたりの灰発生量として，人体，棺，副葬品の化学組成から3.4kg/体と見積もっている[25]．本ケースにおいて集じん灰の発生量は0.48kg/体であったことから，残骨灰の発生量を予測すると2.9kg/体となる．またMonaghanは，イギリスの火葬炉における灰の発生量を1.8〜2.3kg/体と報告している[26]．火葬の状況は遺体の年齢や体格等によっても異なってくるためばらつきはあるものの，残骨灰発生量のヒアリング値である3kg/体は妥当な範囲にあると考えられる．

以上の結果から，残骨灰，および集じん灰中の主たるクロム源としては，ステンレス製架台による可能性が高いことが推測された．また全クロム量としては集じん灰よりも，残骨灰中に移行する割合が大きいことが示唆された．ただし，この施設Kにおける集じん灰について，土壌汚染対策法に基づいた溶出量試験を実施した結果，六価クロムの溶出量は15mg/Lであり，残骨灰へ移行する割合が多くとも，溶出量基準:0.05mg/Lを大幅に超過する結果となった．

b) ステンレス製架台の影響

以上の検討から，残骨灰，集じん灰中のクロムの由来としては，ステンレス製架台であると推定された．そこで，ステンレス製架台を利用していない海外の火葬炉Lにおいて，残骨灰，集じん灰をサンプリングし，溶出量を評価した．

火葬炉Lにおける残骨灰，集じん灰の溶出量試験の結果を，(1)基礎調査の10検体の残骨灰，集じん灰の結果とあわせて**図-5**に示す．L残骨灰，およびL集じん灰の溶出量は，7.0mg/L，および3.4mg/Lであり，基礎調査の結果と比較して，全体的には低い傾向にあったが，E残骨灰，I残骨灰，E集じん灰ほど低くはならず，依然として溶出量基準:0.05mg/Lを大幅に超過していた．すなわち，全クロムのマスバランスからはステンレス製架台が主たるクロム源であると推測されたが，ステンレス製架台がなくとも，溶出量基準の達成は難しいといえる．ステンレス製架台以外のクロムの由来としては，炉内耐火物や熱電対など，比較的対策を取り易い火葬炉内の材質に加え，副葬品などの可能性が考えられ，ステンレス製架台ほどではないが，残骨灰，集じん灰中のクロムに影響をおよぼしていると考えられた．

今後，クロムを火葬炉材質から徹底的に排除したケースにおける，灰中の六価クロムの19号含有量や溶出量について調査していかなければならないが，この場合においても，含有量基準，溶出量基準を超過してしまう可能性が高い．よって，今後，バグフィルター等による集じんをしっかり行い火葬炉外への大気への排出を抑制し，不溶化処理等，別途灰の処理を検討することも必要と考えられる．
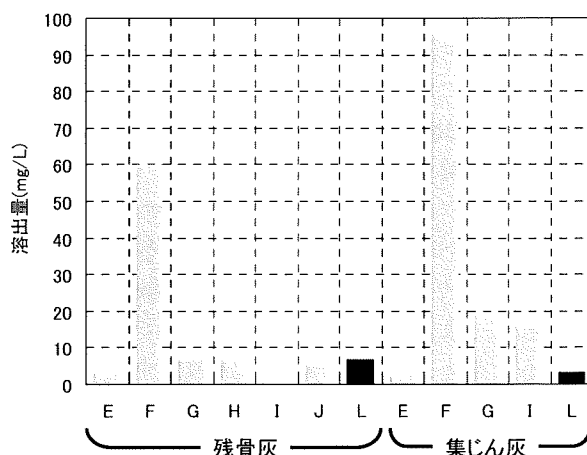

図-5　施設Lにおける残骨灰，集じん灰の六価クロム溶出量の比較

4. まとめ

本研究は，複数の施設の火葬炉を対象に，残骨灰，および集じん灰中六価クロムの排出実態を明らかにするとともに，クロム源とされるステンレス製架台についても調査し，排出抑制対策について検討した．以下に得られた知見を示す．

・火葬炉における残骨灰，集じん灰の六価クロム溶出量は，10検体全てにおいて土壌汚染対策法により規定されている溶出量基準(0.05mg/L)の10〜1,900倍の濃度が検出された．一方19号含有量に関しては，含有量基準(250mg/kg)を超過したのは3検体のみであった．したがって，特に灰の溶出量に注意する必要がある．

・残骨灰，集じん灰の六価クロム溶出量，19号含有量の関係から，多くのサンプルで，19号含有量のほとんどが溶出量試験で溶出していることがわかった．よって，溶出量を抑制するためには，まず，19号含有量を抑制しなければならないことが示唆され，それでも依然として溶出量が基準を超過する場合には不溶化処理が必要であると考えられた．

・排ガスの酸素濃度が比較的低く，CO濃度が高い場合には，六価クロムの19号含有量が高くとも溶出量が比較的抑制されるケースも見られたが，依然として溶出量基準は超過しており，炉内の雰囲気制御等の対策には限界があると考えられる．

・排ガス測定データと，六価クロムの19号含有量から，火葬炉から排ガス経由で大気へ排出される六価クロム量（19号含有量ベース）を推定したところ，集じん機としてバグフィルターや高度排ガス処理設備が導入されることで，集じん機がない場合に比較し，78〜99%程度の排出抑制効果があることが推定された．

・火葬における大気への全クロムの排出係数を求め，他の燃焼発生源と比較したところ，排ガス処理のないケースにおいて，石炭火力発電所，下水汚泥焼却，廃棄物焼却よりも高くなる可能性があり，ステンレス製架台の影響が示唆された．

・灰中の六価クロムの由来として，ステンレス製架台とした場合の，火葬炉1施設における全クロムのマスバランスを明らかにし，その整合性を概ね確認できた．またこの結果から，灰中六価クロムの主たる由来としてはステンレス製架台が損耗し，それらが灰中に移行したものであると推測された．

・ステンレス製架台を用いない海外の火葬炉1施設において，残骨灰，および集じん灰の溶出量を評価したところ，基礎調査の結果に比較して低い範囲にあったが，依然として溶出量基準を超過する結果となった．したがって，ステンレス製架台がなくとも，他のクロム源の影響により，溶出量基準の達成は厳しい状況にあるといえる．

・今後，材質による対策として，クロムを火葬炉材質から徹底的に排除したケースにおける，灰中の六価クロムの19号含有量や溶出量については調査していかなければならないが，この場合においても，含有量基準，溶出量基準を超過してしまう可能性が高い．したがって，バグフィルター等による集じんをしっかり行い火葬炉外の大気への排出を抑制し，不溶化処理等，別途灰の処理を検討することが必要である．

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Measures and Source to Prevent the Emission of Hexavalent Chromium Compounds in Ash from Crematoriums in Japan

Nobuo TAKEDA[1], Masaki TAKAOKA[2], Kazuyuki OSHITA[2] and Shoji EGUCHI[3]

[1]Eco-Technology Research Center, Ritsumeikan University
[2]Department of Urban and Environmental Engineering, Graduate School of Engineering, Kyoto University
[3] Taiyo Chikuro Industries Co. Ltd.

This study measured hexavalent chromium compounds in the fly ash and bottom ash from a number of crematoriums in Japan, and investigated the stainless steel trestle as the source of the chromium, to evaluate the emissions from crematoriums.

The hexavalent chromium compounds leached from all of the ash samples exceeded the Japanese environmental quality standards for soil by 10 to 1,900 times. Based on the consistency of the mass balance of chromium in the crematorium, the estimated source of the chromium was mainly the wear of the stainless steel trestle. Nevertheless, the hexavalent chromium compounds leached from ash samples from a crematorium that did not use a stainless steel trestle were not low enough to meet the Japanese environmental quality standards for soil. Future studies need to investigate ash treatment from crematoriums using bag filters to limit emissions.

**Atmospheric
Chemistry
and Physics**

Mercury emission from crematories in Japan

M. Takaoka[1], K. Oshita[1], N. Takeda[2], and S. Morisawa[1]

[1]Department of Urban and Environmental Engineering, Graduate School of Engineering, Kyoto University, Nishikyo-ku, Kyoto, 615-8540, Japan
[2]Eco-technology Research Center, Ristumeikan University, 1-1-1 Nojihigashi, Kusatsu, Shiga, 525-8577, Japan

Abstract. Anthropogenic sources of mercury emissions have a significant impact on global pollution. Therefore, finding uncharacterised sources and assessing the emissions from these sources are important. However, limited data are available worldwide on mercury emissions from crematories. In Japan, 99.9% of dead bodies are cremated, which is the highest percentage in the world, and more than 1600 crematories are in operation. We thus focused on emissions from crematories in Japan. The number of targeted facilities was seven, and we used continuous emission monitoring to measure the mercury concentrations and investigate mercury behaviour. The total mercury concentrations in stack gases were a few $\mu g/Nm^3$ (normal cubic meters). Considering the time profile of mercury and its species in cremations, the findings confirmed that the mercury in stack gas originated from dental amalgam. The amount of mercury emissions was calculated using the total concentration and gas flow rate. Furthermore, the annual amount of mercury emission from crematories in Japan was estimated by using the total number of corpses. The emission amount was considerably lower than that estimated in the United Kingdom. From statistical analyses on population demographics and measurements, future total emissions from crematories were also predicted. As a result, the amount of mercury emitted by crematories will likely increase by 2.6-fold from 2007 to 2037.

1 Introduction

Given in its high volatility, mercury is emitted into the atmosphere from both anthropogenic and natural sources. Subsequently, it enters oceans, lakes, and rivers from the atmosphere directly or from deposits in surrounding basins, even when no specific source of the element is present (Fitzger-

ald et al., 1998). Some of the inorganic mercury in water is converted into organic mercury, which can be very toxic and is subject to biological accumulation. Consequently, the emission of mercury is of great concern. The United Nations Environment Programme (UNEP) is conducting studies with the goal of a worldwide reduction in mercury (UNEP Chemicals, 2002). These programmes require estimates of the national emissions of mercury from major sources in each country. A report by the Arctic Monitoring and Assessment Programme and UNEP Chemicals (2008), lists mercury emissions from crematories because dental amalgam contains a significant amount of mercury.

According to the Ministry of Health, Labour and Welfare (MHLW) of Japan (2008a), 99.9% of all bodies (1 108 334) were cremated in about 1600 facilities in 2007; this percentage is the highest in the world. With demographic changes, the number of deaths is increasing, and the number of cremations will also increase (MHLW, 2008b). For religious reasons, mercury emissions from crematories in Japan are not regulated by the Air Pollution Control Act or the Waste Management and Public Cleansing Act. However, examining mercury emissions from crematories is needed to determine their environmental impact and to take measures to reduce or monitor them if necessary. Anthropogenic sources of mercury emissions have a significant impact on global pollution. Therefore, finding uncharacterised sources and evaluating the emissions from them are important. However, only limited data on mercury emissions from crematories are available in the literature. According to the Department for Environment, Food and Rural Affairs (DEFRA) in the United Kingdom (2004), mercury emissions in 2020 will be 1.67 times those in 1995 and will peak in 2035. It will contribute 11–35% of the total mercury emissions in the United Kingdom in 2020. In Sweden, it was estimated to be the third highest contributor of all anthropogenic sources of mercury (Hogland, 1994). Emissions from crematories are also very likely to have a significant impact in Japan.

Correspondence to: M. Takaoka
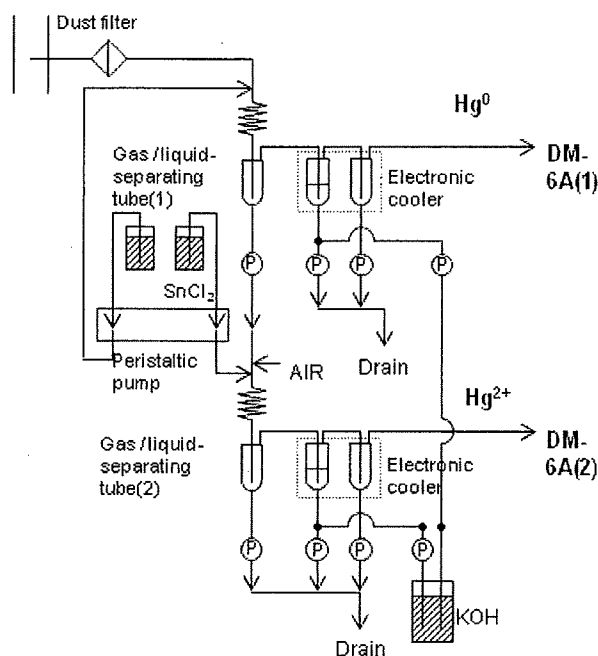(takaoka@environ.mbox.media.kyoto-u.ac.jp)

Fig. 1. The pretreatment section of the speciation CEM.

The purposes of this research were to measure actual emission levels, estimate emissions from crematories in Japan using measurement data and clarify the behaviour of mercury in crematory flue gas with the goal of predicting the environmental fate of the mercury in the surrounding area. Finally, future trends in emissions were estimated.

2 Materials and methods

2.1 Facilities

Table 1 shows the configuration of the seven crematories and the sampling conditions. In Japan, to prevent dioxin emissions from crematories, a guideline was implemented in 2000 requiring installation of air pollution control devices (APCDs) in newly constructed facilities. Although the removal efficiency of mercury by APCDs is beyond the scope of this research, APCDs do have a significant impact on the mercury concentration in final flue gas. Thus, we selected three crematories (Facilities No. 1, 2, and 3) that were constructed after 2000. In these particular facilities, bag filters were used as dust collectors and advanced APCDs had been installed. Additionally, Facility No. 7 also has a bag filter system, although it was constructed in 1998. Conversely, Facilities No. 5 and 6 were not equipped with even a dust collector. All crematories had a series of one secondary combustion chamber to one main combustion chamber, and in all cases, flue gases were cooled by air ejectors. Facility No. 1 used a heat exchanger for flue gas cooling. Natural gas and

oil were used as auxiliary fuel in four (Facilities No. 1, 2, 4, and 7) and three (Facilities No. 3, 5, and 6) of the crematories, respectively.

The origin of the mercury is believed to be dental amalgam (Mills, 1990). Since there is a large difference in mercury emissions between a body with or without mercury amalgam, we conducted many measurements at two facilities (No. 6 and 7) to determine an accurate average mercury concentration. In other crematories, flue gas was sampled twice for each crematory. Since bodies are cremated individually, flue gas was sampled throughout a cremation, from ignition of the secondary burner to extinction of the main burner.

2.2 Mercury emission monitoring

Knowing the species of mercury in stack gas will contribute to a better understanding of the environmental fate of mercury. The mercury concentrations in stack gas were monitored continuously using a speciation mercury continuous emission monitor (CEM, MS1A+DM-6A; Nippon Instruments). This device was developed by Nippon Instruments and the Central Research Institute of the Electric Power Industry in Japan (Chua et al., 2003). The pretreatment section of the speciation CEM is shown in Fig. 1.

An aqueous solution of 1 mol/L potassium chloride and flue gases that had been passed through the dust filter is mixed with a gas/liquid contact coil to transfer oxidised mercury (Hg^{2+}) into the liquid phase. The gas flow rate is 0.5 L/min, and the gas and solution are separated in the gas/liquid separating tube. Elemental mercury (Hg^0) in the gas phase is washed with 1 mol/L potassium hydroxide to remove any acid gas, and the excess moisture in the gas is condensed with an electric cooler. Then, the gas including Hg^0 is fed into the first detection device, which is an atomic absorption mercury analyser (DM-6A(1)). The aqueous solution in the gas/liquid separating tube is directed into another gas/liquid contact coil and then mixed with 1% stannous chloride and 10% sulphuric acid. In this process, the Hg^{2+} in solution is reduced, liberating gaseous Hg^0, which passes through another gas/liquid separating tube before it is fed into the second detection device (DM-6A(2)) to quantify the Hg^{2+}. Here, the gas flow rate must be the identical to that in line DM-6A(1).

Given this speciation, CEM was developed based on the Ontario Hydro method, which is used to determine the elemental, oxidised, particle-bound and total mercury emissions from coal-fired stationary sources (ASTM D6784-02, 2008); it was compared with the Ontario Hydro method periodically and showed an excellent correlation for mercury concentrations ranging from 0 to 100 µg/Nm³ in a municipal solid waste incinerator (Chua et al., 2003). The detection limit of this device is 0.1 µg/Nm³.

Some flue gas obtained at Facility No. 7 was simultaneously sampled using an absorption method based on Japanese Industrial standard K0222. Flue gas was passed through

Table 1. The configurations and mercury concentration of seven crematories.

| Facility No.	1		2		3		4		5		6	7
Dust collector	Bag filter		Bag filter		Bag filter		Electrostatic precipitator		–		–	Bag filter
Advanced APCD	Catalytic reactor		Catalytic reactor		Activated carbon filter		–		–		–	–
Flue gas cooling device	Heat exchanger +air ejecor		Air ejector		Air ejector		Air ejector		Air ejector		Air ejector	Air ejector
Ventilation	Induced		Induced		Induced		Induced		Induced		Induced	Induced
The number of secondary chambers connected to flue gas treatment line	2		2		2		3		2		1	2
Fuel	Natural gas		Natural gas		Kerosene		Natural gas		Kerosene		Kerosene	Natural gas
Experimental No.	1	2	1	2	1	2	1	2	1	2	44	33
Cremation time	58	57	66	59	48	68	64	45	71	66	84 (60–107)	57 (47–75)
Age	64	75	91	79	98	85	66	80	84	65	81 (52–99)	77 (29–101)
Sex	female	female	female	female	female	female	male	female	female	male	male(24), female(20)	male(22), female(11)
Hg concentraion $(\mu g/Nm^3)$	0.2	0.9	0.3	0.4	0.4	3	30.3	1.4	2.8	0.3	3.0 (0.2–82.7)	4.3 (0.8–25.2)
Hg^0 concentraion $(\mu g/Nm^3)$	0.1	0.5	0.2	0.1	0.3	2.7	30.1	1.3	2.7	0.2	2.6 (0.1–81.2)	2.2 (0.0–23.6)
Hg^{2+} concentraion $(\mu g/Nm^3)$	0.1	0.4	0.1	0.3	0.1	0.3	0.3	0.1	0.1	0.1	0.5 (0.1–2.7)	2.1 (0.7–8.1)

a glass filter and bubbled through a sulphuric acid solution with potassium permanganate (KMnO₄). Mercury absorbed in the solution was measured using a frameless reduction vapourisation atomic absorption mercury analyser (RA-2; Nippon Instruments). The sulphuric acid solution with KMnO₄ oxidises organic or inorganic mercury into bivalent mercury ions, and using stannous chloride as a reducing agent, bubbling changes ions into mercury vapour. This mercury vapour is then directed to an absorption cell and atomic absorption was measured at a wavelength of 253.7 nm to determine the quantity of mercury.

Carbon monoxide (CO), oxygen (O_2), carbon dioxide (CO_2), nitrogen oxide (NO_x), and sulphur dioxide (SO_2) concentrations were also monitored using continuous emission monitors (CGT-7000 for CO, NOA-7000 for O_2 and NO_x, SOA-7000 for SO_2; Shimadzu Co. Ltd.). In crematory No. 7, the HCl concentration was measured manually based on Japanese Industrial Standard K0107.

3 Results and discussion

3.1 Mercury concentration in crematory flue gas

First, we show the relationship between the JIS and CEM methods in Fig. 2. As a result, the regression equation is as follows:
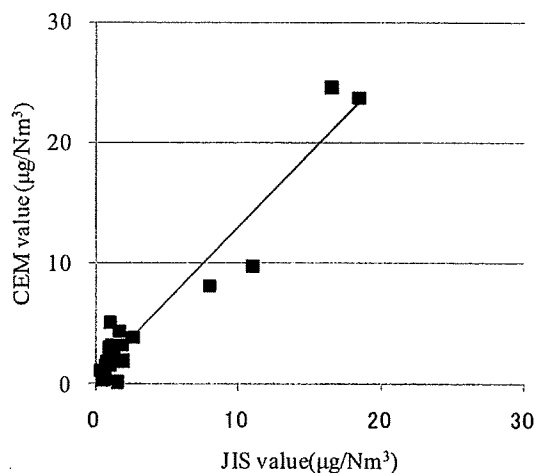
Fig. 2. The relationship between the JIS and CEM methods.

$$CEM = 1.23(JIS) + 0.687 (R^2 = 0.93), \qquad (1)$$

where CEM = CEM value $(\mu g/Nm^3)$; JIS = JIS value $(\mu g/Nm^3)$.

Although the CEM values were slightly higher than the JIS values, the correlation coefficient was considered to be sufficiently high to determine trends in mercury emissions.
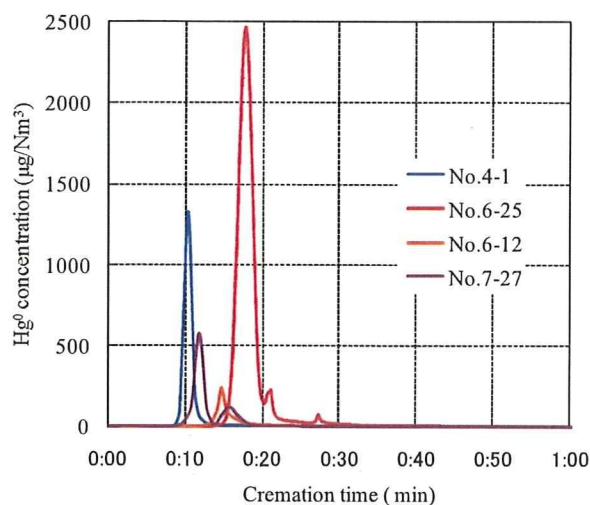
Fig. 3. Temporal changes in the elemental mercury (Hg^0) concentration in crematory flue gas.

When using the CEM value, we may need to be aware of some degree of overestimation.

The total averaged mercury concentration in stack gas was $3.6 \mu g/Nm^3$, which consisted of Hg^0 ($2.6 \mu g/Nm^3$) and Hg^{2+} ($1.1 \mu g/Nm^3$). Hg concentrations ranged from 0.2 to $82.7 \mu g/Nm^3$. When the concentration was normalised by 12% O_2 to compare the concentration to municipal solid waste incinerator flue gas, the total averaged mercury concentration was $17.8 \mu g/Nm^3$, which was higher than that in stack gas of a municipal solid waste incinerator (Takaoka et al., 2002). This is because the O_2 concentration is so high (15.8–20.8%) that the concentration normalised by 12% O_2 becomes high. The mercury concentrations for the facilities are shown in Table 1. The average mercury concentration by facility ranged from 0.4 to $15.9 \mu g/Nm^3$. This difference is not caused by the structure of each crematory, including APCDs, but depends on whether the body contains mercury amalgam.

Mercury concentrations in 22 crematory flue gas samples at three crematories, A, B, and C, were measured in the United Kingdom (Edwards, 2001). According to the reports, the average mercury concentrations normalised by 11% O_2 were 690, 880 and $430 \mu g/Nm^3$ at crematory A, B and C, respectively. The mercury concentration in flue gas is influenced by the volume of exhaust gas per cremation. The average flue gas volume varied considerably by crematory; indeed, the range was $3250–14600 Nm^3/h$. The average volume of exhaust gas in a cremation in Japan is 3–10 times larger than that in the United Kingdom because the flue gas was cooled by air dilution using an air ejector in Japan. However, this means that the mercury concentration in the UK exhaust gas is very high by comparison. Hogland (1994) reported the mercury concentration from a crematory in Lund,

Sweden. Although the volume of exhaust gas was about 1/5–1/20 of that in Japan, the maximum concentration achieved was $60\,000 \mu g/Nm^3$, which is extremely high. From comparisons with data for other countries, we suggest that the average mercury quantity emitted in Japan is low.

The contribution of Hg^0 to the total mercury was 70%, which is relatively high. Hg^0 concentrations ranged from 0.1 to $81.2 \mu g/Nm^3$, whereas Hg^{2+} concentrations ranged from 0.1 to $8.1 \mu g/Nm^3$. A higher peak was observed only in Hg^0.

The chemical form of mercury in flue gas is known to be influenced by the gas composition, especially the presence of halogen compounds (Takaoka, 2005). HCl was measured in Facility No. 7, and its concentration was found to range from 2 to $13 mg/Nm^3$. Even when the HCl was removed by a bag filter (this facility did not use alkaline reagents for acid gas removal), the concentration was very low compared with that in the municipal solid waste incinerator. To check the validity of the mercury form from the viewpoint of thermodynamics, the stable form of mercury was calculated under the following conditions: 19.6% O_2, 10 ppm HCl and 4% H_2O using Fact sage 5.0. As a result, $HgCl_2$ was found to be stable at 200 °C and Hg^0 to be dominant at temperatures above 600 °C. Because Hg^0 was dominant in flue gas based on measurement results, there was a difference in the chemical form between the results of thermodynamics and measurements. It might be cleared by measurement in upstream flue gas before bag filter.

3.2 Temporal change in mercury concentration

Two patterns in changes of mercury concentrations were observed. The first pattern is shown in Fig. 3. In some samples, a large peak in Hg^0 appeared at 10–20 min; two samples exceeded $1000 \mu g/Nm^3$. This period indicates the burning of the cephalic part of the corpse. Considering the behaviour of mercury in cremations, the findings confirmed that the mercury in stack gas originated from the mercury in dental amalgam. This behaviour was previously reported by Hogland (1994). During this period, peaks were observed in 36 samples.

In the other pattern, no distinct peak of Hg^0 was detected in the remaining 51 samples. In some samples, a small peak of Hg^{2+} was noted. Various internal organs of the human body contain mercury, and the mercury quantity in an adult is estimated to be more than 3.3 mg/body, apart from dental amalgam (The Chemical Society of Japan, 1977). Moreover, the mercury contents of liver (0.71 mg) and kidney (0.28 mg) are reportedly quite high. If these organs are burned in a short time, calculations indicate that a small peak (about 1–$3 \mu g/Nm^3$) may appear. From comparisons of the measurements and the above calculations, we can conclude that mercury in dental amalgam has a significant impact on mercury emissions from crematories.
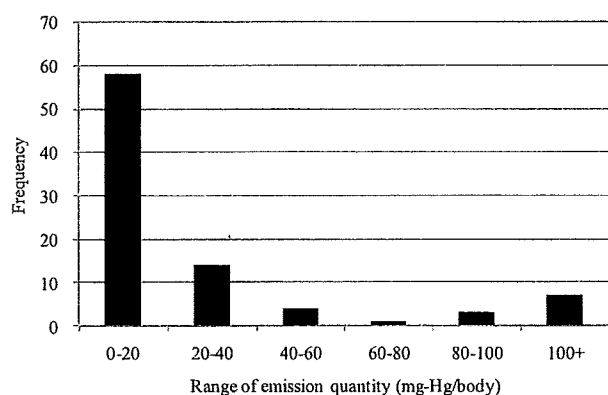
Fig. 4. The distribution of emission quantities calculated using measured data.

3.3 Mercury emission from crematories

Total emissions from all active crematories in Japan were estimated using the following equations:

$$\text{Total emissions (mg/year)} = \text{Emission quantity (mg/body)} \times \text{the number of cremations (bodies/year)} \tag{2}$$

Emission quantity (mg/body)

$= \text{Mercury concentration (mg/Nm}^3)$

$\times \text{dry gas volume (Nm}^3/\text{h)}$

$\times \text{cremation period (h)/the number of cremations (bodies)}$

$$\tag{3}$$

The amount of mercury emission was calculated to be 31.7 mg/cremation using the total concentration and gas flow rate. The standard deviation was 64 mg/body; this was so large because the mercury quantity per body has a large range from 0.7 to 362 mg/body. In the United Kingdom, 150 mg/four cremations was proposed as a regulatory criterion by DEFRA (2004). Taking this to be equivalent to 37.5 mg/body, the values in 15 samples in this research were over this level.

The distribution of emission quantities calculated using measured data is shown in Fig. 4. As the emission quantity increases, the frequency decreases. However, the frequency increased at over 80 mg/body. In the United Kingdom, in total, 54 cremations were tested at two separate locations (Rahill, 2008). From the results, 31 cremations were suspected to have been of bodies with no amalgam fillings. Average mercury release per cremation over 54 cremations was reported to be 240 mg/body. The United States Environmental Protection Agency (US EPA) also reported that the emission quantity was 456 mg/body from nine cremations (Rahill,
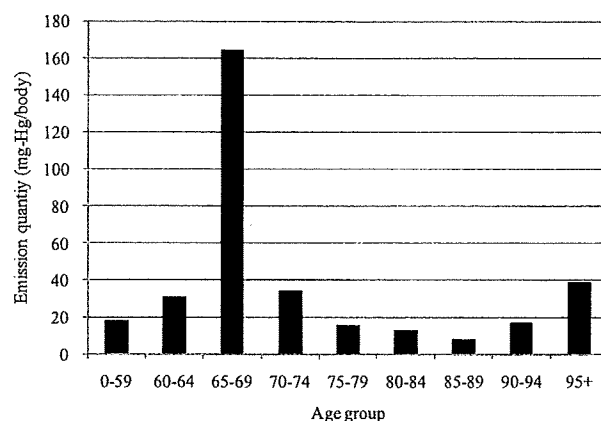

Fig. 5. The amount of mercury emission per cremation calculated using measured data by age group (number of samples by age group: 0–59:4, 60–64:6, 65–69:7, 70–74:9, 75–79:15, 80–84:17, 85–89:9, 90–94:12, 95+:8).

2008). Although 0.94 mg/body was reported in another US EPA document, this value would have been for bodies with no amalgam filling (US EPA, 1997). According to the UNEP tool kit for the identification and quantification of mercury releases (2005), the emission quantity in various countries ranged from 0.1 to 5.1 g/body. Comparing our results with these reported data, including corpses with amalgam fillings, the emission quantity obtained in this research is quite low. The use of amalgam has a close relationship with mercury emissions. The amount of mercury in amalgam in one filling was reported to be 600 mg by Mills (1990). We sought to examine the actual mercury content in one used amalgam filling. According to our ongoing research, the weight per filling removed by a dentist ranged from 56 to 231 mg. The mercury content in an amalgam filing ranged from 42.5 to 53.0%. Therefore, the average amount of mercury per filling was 51.6 mg. This is at least one of the reasons why emissions in Japan are low.

The amount of mercury emission per cremation calculated using measured data by age group is shown in Fig. 5. The maximum value was obtained in the age range 65–69 years. The second highest value was observed in the age ranges of 95+, 70–74, and 60–64 years. In addition, a difference in mercury emission was observed between males and females. This trend is consistent with a report from the United Kingdom (Edwards, 2001).

These mean values (31.7 mg/body) were multiplied by 1 169 174, the number of bodies cremated in 2007, which was calculated using the number of corpses (1 108 334 including dead bodies of uncertain age (MHLW, 2008b)) and the cremation rate (99.9%); total emissions were estimated to be 35.1 kg/year. Considering the number of bodies and the emission quantity by age group, the total estimated emissions decreased slightly to 32.5 kg/year. This constitutes less
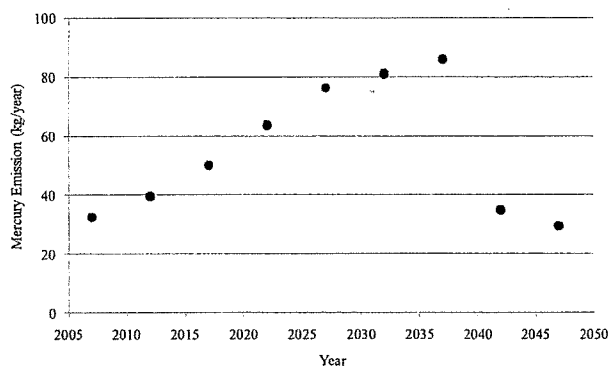
Fig. 6. Estimated future trends of total mercury emissions in Japan from crematories based on population demographic statistics and measured data.

than 0.01% of the total amount of mercury released into the atmosphere (21–28 tons/year) in Japan (Kida et al., 2008).

To estimate mercury emissions in the United Kingdom, 3 g/body was used as the emission quantity (DEFRA, 2004). This value is based on Mills' report (1990), which assumes that a dead body has five restored teeth with amalgam fillings containing 0.6 g mercury. Based on this assumption, the mercury emission was calculated to be 3300 kg/year in Japan. This procedure leads to an obvious overestimation. The mercury release to the air from crematories should be based on measurements.

Next, total future trends in emission were calculated using statistics on population demographics (NIPSSR, 2008) and the emission quantity obtained in this research. That is, the emission quantity was multiplied by the number of dead bodies by age group. Here, we assume that the emission quantity obtained in this research is a property of each group and shifted it to the emission quantity of the next age range as 5 years passed. We set the cremation rate to be 100%. As a result, estimated future trends of total mercury emissions from crematories based on the statistics of population demographics and measured data are shown in Fig. 6. The amount of mercury emissions from crematories is expected to increase to 86 kg/year, about 2.6-fold, between 2007 and 2037. The distinct distribution of emission quantities is expected to show a rapid decrease in 2042 because the highest emission quantity (164 mg/body) moved outside the age ranges. In fact, the distribution of emission quantities would then be expected to moderate and then decline because of the impact of dental care, such as the removal of amalgam fillings, the loss of teeth and loss of mercury in amalgam fillings (Skare, 1995) as the age group shifts. Although we should use measurement data to estimate current emissions, we can combine measurement data with demographic statistics on dental care or material flow data of mercury amalgam to estimate accurate future trends in mercury emissions from crematories.

4 Conclusions

In this study, to measure the actual emission level and estimate the emission from crematories in Japan using measurement data, the mercury concentration in crematory flue gas from mercury emissions was examined at seven facilities. Total averaged mercury concentration in stack gas was $3.6\,\mu g/Nm^3$, which consisted of Hg^0 at $2.6\,\mu g/Nm^3$ and Hg^{2+} at $1.1\,\mu g/Nm^3$. The mercury concentration ranged from 0.2 to $82.7\,\mu g/Nm^3$. At two facilities, we used continuous emission monitoring to measure mercury concentrations and to evaluate mercury behaviour. In some samples, a large peak of Hg^0 appeared at 10–20 min. Considering the behaviour of mercury in cremations, the findings confirmed that mercury in stack gas originated from dental amalgam. The amount of mercury emitted was calculated to be 31.7 mg/cremation using the total concentration and gas flow rate. The emission quantity obtained in this research is apparently quite low. Although the reason for this is unclear, the mercury amount per filling in the Japanese oral cavity may be smaller than that in other countries. Furthermore, the annual amount of mercury emission from crematories in Japan was estimated using the total number of corpses. The total emissions were estimated to be 35.1 kg/year. Total future trends in emissions were calculated using demographic statistics and the emission quantity obtained in this research. As a result, the amount of mercury emissions from crematories is expected to increase by 2.6-fold between 2007 and 2037.

One possible countermeasure would be to remove amalgam fillings before cremation, but this may be difficult to actualize for practical and religious reasons.

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