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## End-of-life vehicle recycling and automobile shredder residue management in Japan

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**Abstract** The Japanese Government introduced the Law on Recycling of End-of-Life Vehicles (ELV Recycling Law) in 2002. This law requires manufacturers to retrieve chlorofluorocarbons (CFCs), airbags, and automobile shredder residue (ASR) from ELVs and to properly recycle the remaining materials. This framework is compared with European ELV directives. Pilot-scale incineration plant testing has revealed a greater formation of by-product persistent organic pollutants (POPs) during the primary combustion of ASR compared to normal municipal solid waste. This may be attributed to the abundance of chlorine, Cu, and Fe in ASR, as Cu and Fe have been found to catalyze the formation of POPs under certain conditions. However, most by-product POPs were destroyed by the secondary combustion, and almost all were removed after flue gas treatment. The direct melting system is a shaft-type gasification and melting technology that has proved effective in many municipal solid waste applications. This system can be applied to ASR recycling for effective decomposition of brominated flame retardants and polybrominated dioxins.

**Key words** End-of-life vehicle (ELV) · Automobile shredder residues (ASR) · Brominated flame retardant · Thermal process · Recycling

### Introduction

The management of end-of-life vehicle (ELVs) and the appropriate treatment of the recycling residues are the subject of worldwide concern. ELVs are mainly recycled for

iron production through the processes of dismantling and shredding. In the initial disassembly process, reusable parts such as engines, batteries, and recyclable materials are retrieved by hand. In the subsequent shredding process, iron and aluminum scrap is collected by magnetic/wind separation. The iron scrap collected is recycled in the process of secondary iron production or in an electric furnace.

Annual sales of new vehicles in Japan are about 6 million, and the total number of vehicles with ownership amounts to about 80 million. The present status of ELV management in Japan is as follows.<sup>1,2</sup> Annually, approximately 5 million of the 80 million vehicles are discarded, of which about 1 million are exported. Discarded cars are delivered from about 50 000 used-car dealers and about 80 000 maintenance centers to dismantling companies. After about 5 000 disassembly companies have collected parts such as engines, tires, and batteries, the remaining material of the vehicles, about 60% of the total weight, is delivered to shredding companies. About 140 shredding companies separate iron by shredding and magnetism and then sell the iron as scrap. The shredding process produces automobile shredder residues (ASR), and these shredder residues account for 20%–25% of the original weight of the car. Approximately 700 000 tons of ASR is generated annually, and this has mainly been disposed of as landfill. However, because the landfill capacity for final disposal has become limited, a reduction in ASR has become all the more important. In order to establish a system for recycling and appropriate treatment, the Law for the Recycling of End-of-Life Vehicles (ELV Recycling Law) was enacted in July 2002. Under the law, automobile manufacturers are obliged to collect and recycle air bags and ASR generated during the processing of ELVs. Chlorofluorocarbons (CFCs) also should be recovered and destroyed. The target recycling rate for ASR is 70% by fiscal year 2015. Therefore ASR has been increasingly subject to material recycling and the methods of thermal recovery.

Because ASR contain heavy metals and persistent organic pollutants (POPs), proper recycling and management systems are required. Information concerning polychlorinated dioxins/furans (PCDDs/DFs), polychlorinated

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biphenyls (PCBs), hexachlorobenzene (HCB), and polychlorinated naphthalenes (PCNs) from the thermal treatment of ASR is necessary for the appropriate management of these systems, because such POPs are well known by-products of thermal processes.<sup>3,4</sup> However, there has been limited information on POPs arising from ASR. Moreover, to ensure that ELV Recycling Law measures reduce the formation and release of POPs, it is important to know about their formation, destruction, and removal at each stage of the thermal-treatment process. It is a matter of concern that ASR may have a greater capacity to produce by-product POPs than does refuse-derived fuel (RDF) from municipal solid waste, because ASR contains greater quantities of metals such as Cu and Fe, as well as plastics. Cu and Fe are well known to catalyze the chlorination of organic compounds.<sup>5,6</sup>

In the present study, we carried out experiments to investigate the unintentional formation, decomposition, and emission-control performance of POPs during ASR or RDF incineration, and we discuss the behavior of POPs at several stages of the thermal-treatment process. The direct melting system (DMS) is a shaft-type gasification and melting technology that has proved effective in many municipal solid waste applications. In this system, combustible wastes are gasified and burnt completely in a combustion chamber, after which a heat-recovery system effectively utilizes the energy. Incombustible wastes are completely melted in the coke-bed of the melting furnace at high temperature, allowing all slag and metal by-products to be effectively utilized as resources. This system can also be applied to ASR. In this article we also compare the Japanese framework for the recycling of ELVs with the European ELV Directive.

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## ELV recycling policy developments

The Law on Recycling of End-of-Life Vehicles (ELV Recycling Law) was enacted in 2002 in Japan<sup>7</sup> (Table 1). This law requires manufacturers to retrieve CFCs, airbags, and ASR from ELVs and to properly recycle the remaining materials. Dismantling and shredding companies are obliged to properly recycle ELVs and hand over airbags and ASR to manufacturers. Car owners are required to incur the recycling costs when they buy a new car. For cars already bought when the law came into force, car owners must pay the costs at the time of the first car inspection. This recycling law aims at smooth recycling of ELVs in the market. In other words, the duty of collecting CFCs, airbags, and ASR, which requires proper management, is imposed on manufacturers and the costs are borne by consumers.

ELV Directive 2000/53/EC of the European Parliament came into force in 2000.<sup>10</sup> It aims to prevent waste generation from ELVs and to protect the environment through promoting the collection, reuse, and recycling of their components (Table 1). The Directive states the minimum reuse and recovery rates for ELVs as well as the technical requirements for car design. For vehicles produced after 1980, a

reuse and recovery target of 85% on a mass basis (recycling 80%) should have been achieved by 01/01/2006. Operators must meet a reuse and recovery target of 95% by January 2015. In order to increase the recovery and recyclability of vehicles, bans were also introduced on heavy metals such as lead, mercury, cadmium, and hexavalent chromium. Smink<sup>8</sup> summarizes the ELV Directive as being based on the principle of extended producer responsibility (EPR) and the subsidiarity principle. Under an EPR scheme, manufacturers are financially or physically responsible for their products after they have been discarded at the end of their useful life. EPR requires that manufacturers either take back their products, with the aim of reusing, recycling, or remanufacturing, or delegate this responsibility to a third party. There are differences in national EPR programs. Subsidiarity means that the implementation of the requirements of the Directive relies on the individual approaches of the Member States, taking into account the local conditions in each country. An example of a more voluntary approach is the marking requirements for components. Gerrard and Kandlikar<sup>11</sup> discuss the impact of the ELV Directive on “green” innovation and vehicle recovery. They point out some obstacles to the widespread adoption of remanufacturing vehicles, of which post-shredder technology is the key point for the economic feasibility of recycling and energy recovery.

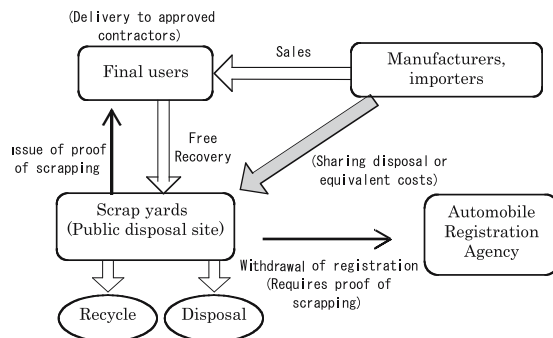
In Japan, the ELV Recycling Law was fully enforced in January 2005 to better cope with ASR, as well as airbags, CFCs, and other new components. In 2005, the first full year following the enforcement of the ELV Recycling Law, approximately 2.7 million vehicles were dismantled and disposed of.<sup>1,2</sup> This was, however, substantially short of the initially forecast 4 million vehicles. Changes in the structure of ELV distribution, such as increased exports of used cars, are believed to be the main reason for the shortfall. Used-car exports are rising each year as a result of more companies becoming involved in the industry and progress in developing overseas sales routes. In total, 371 000 used vehicles were exported from Japan in 2001, and this number had increased to 940 000 by 2005. There is a high demand for used cars from Japan, including older models with low mileage that represent good value in developing nations. Dismantled ELVs produce around 200 kg of ASR per vehicle, so 4 million ELVs represent 800 000 tons of ASR. The estimated 2.7 million vehicles shredded in 2005 would have generated some 500 000 tons of ASR. The increase in facilities raised ASR processing capacity to about 630 000 tons in 2005, exceeding the volume of ASR produced. The target recycling rate for ASR is 30% by fiscal year 2005, 50% by 2010 and 70% by 2015. In fact, the ASR recycling rate in 2005 was 48%–70%.<sup>1</sup>

Vehicle owners pay the fees required for ELV recycling. These are collected when new cars are purchased or when cars are taken in for mandatory periodic inspections. Moreover, the enactment of the ELV Recycling Law coincided with changes in the system for canceling vehicle registrations. Three registration cancellation systems have been introduced: temporary cancellation (with the return of the vehicle inspection certificate in the case of light cars),

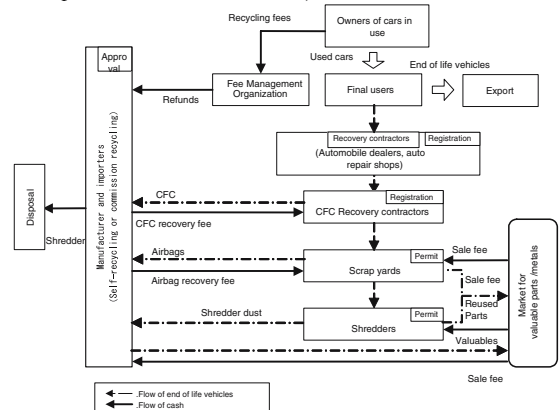
**Table 1.** Comparison of European and Japanese ELV recycling systems

Item	Laws	
	EU	Japan
Law	Directive 2000/53/EC (2000/53/EC)	Law for the Recycling of End-of-Life Vehicles
Date of enactment	2000/10	2002/7
Date of enforcement	Coming into effect through national laws and regulations to comply with the Directive by 2002/4	2005/1
Targeted waste	End-of-life vehicles (ELVs) and their components, materials, and parts	End-of-life vehicles
Background and purposes of enactment	Directive was to harmonize policies for recycling of end-of-life vehicles in member states, to contribute to environmental conservation and energy saving, and to avoid unfair competition within the Community. Other purposes were to promote vehicle manufacturing geared for recycling, regulation of recovery of end-of-life vehicles, environmental standards for scrap yards, and standardization of recycling targets for member states	End-of-life vehicles are valuable resources because they contain usable metals and parts, and recycling has been done in the past. Meanwhile, the reduction of shredder residue has become an issue because industrial waste-disposal sites are reaching their limit. There are also concerns of illegal and improper disposal. Therefore, the Law for the Recycling of End-of-Life Vehicles was enacted to define the roles of the parties involved in the proper management of end-of-life vehicles
Summary of the law	<p>Manufacturers are required to recover vehicles from the final owners, and to share the cost of the measures required by the Directive.</p> <ol style="list-style-type: none"> <li>Reduction of waste <ul style="list-style-type: none"> <li>limitation on use and control of environmental release of toxic substances</li> </ul> </li> <li>Recovery <ul style="list-style-type: none"> <li>establishment of recovery system where current systems for end-of-life vehicles and parts are inadequate</li> <li>recovery of end-of-life vehicles is to be done free of charge to consumers. Cost of recovery is to be shared by the manufacturer</li> </ul> </li> <li>Disposal <ul style="list-style-type: none"> <li>provisions for minimum standards on end-of-life vehicle storage and treatment, treatment of toxic substances, pretreatment for recycling</li> </ul> </li> <li>Reuse and recycle <ul style="list-style-type: none"> <li>recycling rate is to be 80% by average weight by 2006/1/1 reuse and recovery rate is to be 85% by 2006/1/1</li> <li>recycling rate is to be 85% by average weight by 2015/1/1 reuse and recovery rate is to be 95% by 2015/1/1</li> </ul> </li> <li>Identification standards, scrapping information <ul style="list-style-type: none"> <li>identification standards for parts and materials that are to be recycled</li> </ul> </li> <li>Reporting and release of information <ul style="list-style-type: none"> <li>member states are to report to the European Council every 3 years on the progress of their compliance with the Directive</li> </ul> </li> <li>Embodiment of the Directive in national laws <ul style="list-style-type: none"> <li>member states must pass national laws that comply with the Directive by 2002/4/21</li> </ul> </li> </ol>	<p>Manufacturers are required to recover and recycle CFCs, airbags, and shredder residue (ASR), while consumers are required to share the associated costs on purchase of new cars, and upon automobile inspection for cars in use.</p> <ol style="list-style-type: none"> <li>Targeted waste <ul style="list-style-type: none"> <li>end-of-life vehicles</li> </ul> </li> <li>Roles of parties involved <ol style="list-style-type: none"> <li>Manufacturers and importers <ul style="list-style-type: none"> <li>recovery and proper recycling of CFCs, airbags, and shredder dust</li> </ul> </li> <li>Recovery contractors (under prefectural registration) <ul style="list-style-type: none"> <li>recover end-of-life vehicles from final owners</li> </ul> </li> <li>CFC recovery contractors <ul style="list-style-type: none"> <li>delivery of CFCs to automobile manufacturers</li> </ul> </li> <li>Scrap yards <ul style="list-style-type: none"> <li>delivery of airbags and shredder dust to automobile manufacturers</li> </ul> </li> <li>Automobile owners <ul style="list-style-type: none"> <li>delivery of end-of-life vehicles to recovery contractors</li> </ul> </li> </ol> </li> <li>Recycling fees <ul style="list-style-type: none"> <li>cost shared by owners of vehicles</li> <li>recycling fees to be administered by a management corporation</li> </ul> </li> <li>Establishment of data-management system</li> </ol>
Burden of cost	Manufacturers	Consumers. Upon purchase of new vehicles (or upon inspection for vehicles in use)

Recovery system



Consumers. Upon purchase of new vehicles (or upon inspection for vehicles in use)



**Table 1.** *Continued*

Item	Laws	
	EU	Japan
Number of automobiles sold	Number of ELVs in EU countries: 11.3 million (1995), 17 million (2015) <sup>8</sup> ASR: 8 to 9 million tons/year <sup>9</sup>	Number of ELVs: 2.7 million (2005) <sup>2</sup> ASR: 500 000 tons/year Number of manufacturers: 19 companies (2004/12) Scale of market: 13.5 trillion yen (2004), scale of recycling market (including transport costs): 48.1 billion yen (0.35% of market)
Agency responsible	–	Ministry of Economy, Trade and Industry, Ministry of the Environment

CFC, chlorofluorocarbon

**Table 2.** Persistent organic pollutant (POP) characterization of automobile shredder residues (ASR)

POPs	ASR-1	ASR-2	ASR-3
PBDEs (ng/g)	310 000	240 000	110 000
TBBPA (ng/g)	15 000	950	220
HBCD (ng/g)	–	5700	990
TBP (ng/g)	–	68	180
PBDDs/DFs (ng/g)	30	120	10
monoBr-CDDs/DFs (ng/g)	ND	15	ND
PCDDs/DFs (TEQ) (ng TEQ/g)	0.0043	0.38	0.043
Dioxin-like PCBs (TEQ) (ng TEQ/g)	0.027	0.014	0.015
PCBs (ng/g)	270	44	230
PCNs (ng/g)	–	47	13
PAHs (ng/g)	–	34 000	36 000

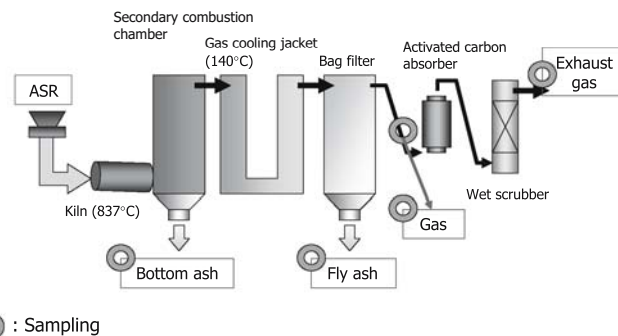
PBDE, polybrominated diphenyl ether; TBBPA, tetrabromobisphenol A; HBCD, hexabromocyclododecane; TBP, tribromophenol; PBDD/DF, polybrominated dioxin/furan; PCDD/DF, polychlorinated dioxin/furan; TEQ, toxicity equivalent; PCB, polychlorinated biphenyls; PCN, polychlorinated naphthalenes; PAH, polyaromatic hydrocarbon; ASR-1, input to direct melting experiment; ASR-2/ASR-3 inputs for laboratory-scale experiments; ND, not detected

permanent cancellation, and annulment for export purposes. Dismantling or export notification is required if a vehicle is to be dismantled or exported after the registration has been cancelled temporarily. Cancellation of registration for export is required if a vehicle is to be exported without temporarily suspending the registration. This modified system was instituted to enable authorities to determine whether a particular vehicle had been dismantled or exported as a used car, and this has made it easier to curtail illegal dumping.

## ASR management and POP behavior

### Characterization of ASR

ASR has the potential to release POPs into the environment as a result of their intentional use in the original products and through the POPs formed as unintended by-products. Concentrations of brominated flame retardants (BFRs), brominated dioxins, chlorinated dioxins, and other contaminants in ASR samples are listed in Table 2.<sup>12,13</sup> ASR contained polybrominated diphenyl ethers (PBDEs) at levels of a few hundred ppm. ASR also contained hexa-



**Fig. 1.** Process flow of incineration pilot plant. ASR, automobile shredder residue

bromocyclododecane (HBCD), tetrabromobisphenol A (TBBPA), and tribromophenols (TBPs) in the range of sub-ppm levels to several ppm. The PBDEs included a high proportion of highly brominated substances, and decabrominated diphenyl ether (DeBDE) is the main PBDE congener. Compared with the municipal solid waste and waste TV sets that we previously investigated,<sup>12,13</sup> the amounts of BFRs such as PBDEs and TBBPA were found to be higher in ASR than in municipal solid waste and lower than in waste TV sets. ASR contained 30 ng/g of polybrominated dioxins/furans (PBDD/DFs), but monobrominated-polychlorinated dioxins/furans (MoBrPCDD/DFs) were not detected. ASR also contained 0.97 ng/g of PCDD/DFs, 30 ng/g of dioxin-like PCBs, and 270 ng/g of PCBs. The brominated dioxins were thought to have originated from impurities contained in BFRs and/or as thermal by-products of the processing of BFR-containing materials.

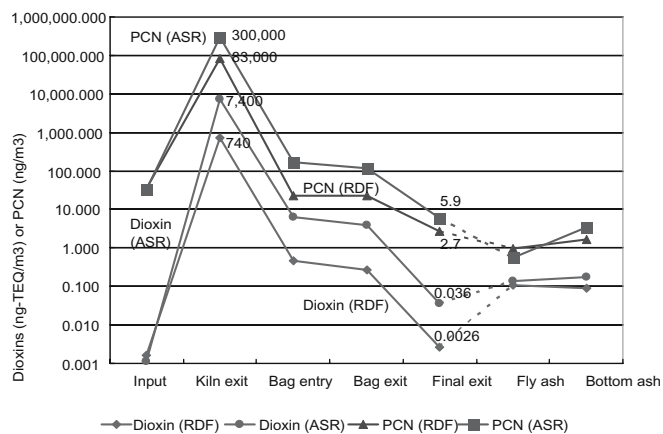
## Thermal behavior of POPs in an ASR incineration system

Recently, ASR has been increasingly planned to be applied to electrical power generation and heat-recovery systems. For the appropriate management of ASR, however, chemical information concerning POPs, present as intentional applications to the original products and/or as by-products of the combustion of ASR, is essential. We previously carried out an incineration experiment in a plant-scale incinerator at the National Institute for Environmental

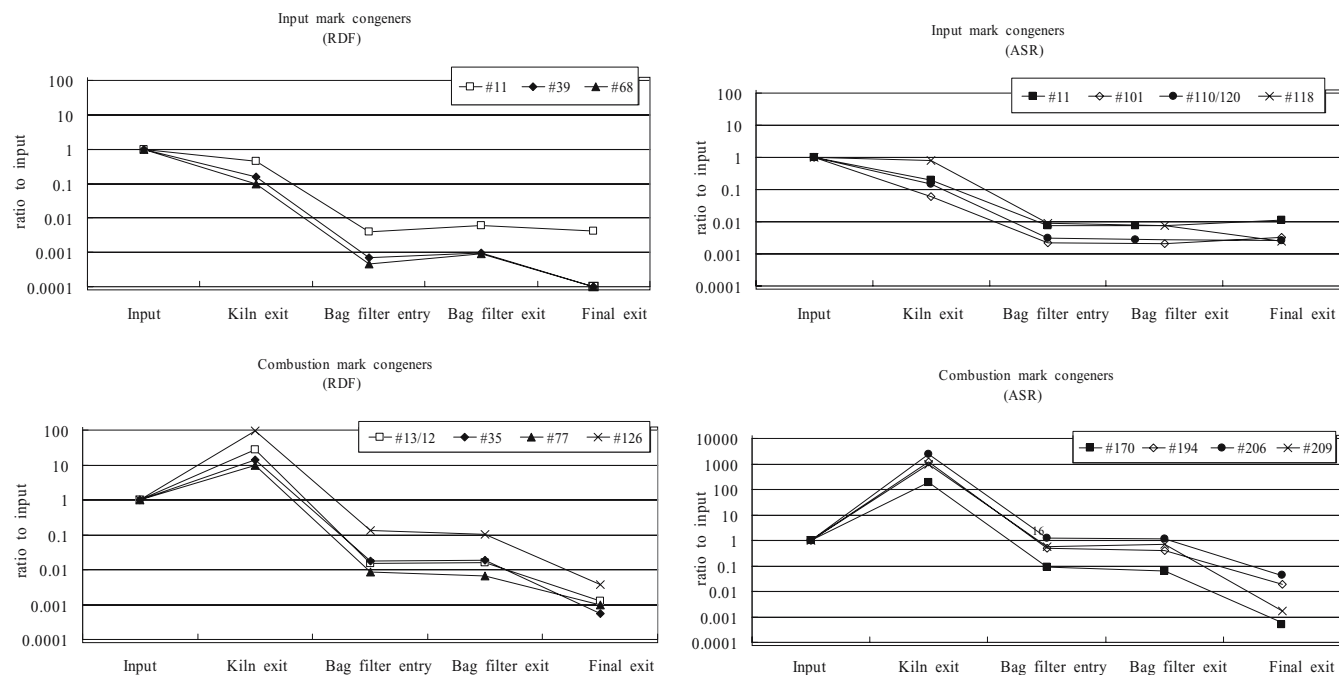
Studies (NIES).<sup>12-14</sup> This incineration system consisted of an electrically heated rotary kiln furnace, an electrically heated secondary combustion chamber, a gas-cooling zone, a bag filter, an activated-carbon adsorption tower, and a wet scrubber (Fig. 1). Details of this pilot plant and the experimental methods used are described elsewhere.<sup>14</sup> We used refuse-derived fuel (RDF) or ASR as input waste samples for the combustion experiments. The RDF samples had particle dimensions of approximately 8mm (diameter) and 25mm (length). The ASR samples contained plastics, textiles, soil/sand, rubber/leather, and wiring, and the pieces were less than 10mm in size. The thermal behavior of dioxins and PCNs is shown in Fig. 2. In the ASR experiments, the concentrations of dioxins, PCBs, HCB, and

PCNs were 7400 (kiln exit) and 0.036ng-TEQ/m<sup>3</sup>N (final exit), 92000 (kiln exit) and 41 ng/m<sup>3</sup>N (final exit), 2200000 (kiln exit) and 4.1 ng/m<sup>3</sup>N (final exit), and 300000 (kiln exit) and 5.9 ng/m<sup>3</sup>N (final exit), respectively. In the RDF experiments, their concentrations were 740 (kiln exit) and 0.0026ng-TEQ/m<sup>3</sup>N (final exit), 8100 (kiln exit) and 14 ng/m<sup>3</sup>N (final exit), 300 (kiln exit) and 1.7 ng/m<sup>3</sup>N (final exit), and 83000 (kiln exit) and 2.7 ng/m<sup>3</sup>N (final exit), respectively. It can be seen that these compounds were formed as by-products in the kiln by combustion. The formation of by-product POPs in the ASR experiments was much greater than that in the RDF experiments. The ratio of formation in the ASR experiments to that in the RDF experiments was 10 for dioxins, 11 for PCBs, 7300 for HCB, and 3.6 for PCNs at the kiln exit.

Concerning the behavior of PCBs, incineration increased not only the concentration of PCBs but also the numbers of congeners.<sup>15</sup> In flue gases at the kiln exit, 206 and 184 congeners were detected on incineration of RDF and ASR, respectively, while 103 and 142 congeners were detected in the RDF and ASR input samples, respectively. Congener-specific analytical methods of PCBs were reported in detail in a former study.<sup>15</sup> These results indicate the formation of numerous by-product PCBs on incineration. The predominant congeners detected in RDF and ASR input samples were #11, #39, and #68 for RDF and #11, #101, #110/120, and #118 (as IUPAC #) for ASR. These congeners were designated as input mark congeners for RDF and ASR (Fig. 3). The predominant congeners detected on incineration of RDF were #13/12 (18.5%), #35 (3.70%), #77 (6.17%), and #126 (3.33%). The congeners detected on incineration of ASR were #170 (6.09%), #189 (3.26%), #194 (9.46%), #195



**Fig. 2.** Behavior of dioxins and polychlorinated naphthalenes (PCNs) in ASR incineration pilot plant. *RDF*, refuse-derived fuel; *TEQ*, toxicity equivalent



**Fig. 3.** Input mark congeners (*upper panels*) and combustion mark congeners (*lower panels*) for RDF and ASR incineration. Congener numbers are according to IUPAC

(3.26%), #196 (4.57%), #206 (15.2%), and #209 (10.9%). These congeners can be designated as combustion mark congeners for PCBs, because they are less abundant in the input samples and in Kanechlor, PCB product in Japan.<sup>16</sup> For comparison of the gas samples with the input samples, we calculated the ratio of the amount of each congener in the gas sample to that in the input. The input ratios for the 26 congeners (#11, #18, #19, #22, #26, #28, #31, #32, #44, #52/69, #54, #68, #70, #80, #87/108, #98/95, #101, #121, #136, #151, #153, #155, and #184) were less than 1.0 at the kiln exit in both the RDF and the ASR experiments. Many congeners whose input ratios were greater than 1.0 were detected at the kiln exit. These results show that both the decomposition and formation of PCBs occurred in the primary combustion chamber. In the incineration of RDF, those congeners with a high input ratio, or which were newly formed during combustion, were #13/12, #35, #77, and #126, which are all non-ortho-CBs. On the incineration of ASR, congeners which had from one to four chlorines in the ortho position were predominantly formed. Most by-product POPs were destroyed during the secondary combustion, and almost all by-product POPs were removed by the flue-gas treatment.

The greater formation of by-product POPs during the combustion of ASR compared to the combustion of RDF may be attributed to the abundance of chlorine, Cu, and Fe in the input samples. The catalytic effect of metals such as Cu and Fe on the chlorination of dioxins is known.<sup>5,6</sup> The chlorine content of RDF and ASR was 0.97% and 2.9%, respectively. The respective Cu contents were 0.056% and 3.4%, while the Fe contents were 1.7% and 2.8%. Thus, each element was more abundant in ASR than in RDF. HCl levels at the entry to the bag filter in the ASR experiment were 410 mg/m<sup>3</sup>N, which was considerably higher than the value of 240 mg/m<sup>3</sup>N obtained in the RDF experiment. We therefore suggest that by-product POPs were formed to a greater extent in the ASR experiment by catalytic chlorination during combustion.

Kim et al.<sup>17</sup> analyzed the mass balance of Korean shredding facilities. In that study, ASR had a composition of 68%–70% iron, 2%–3% nonferrous metals, and 27%–29% shredder dust. The final shredder dust had a calorific value of about 5500 kcal/kg, so that it could be suitable for incineration or gasification. These authors concluded that in order to reach the goal of a greater than 95% recycling rate, the residue must be further recycled using alternatives such as gasification and melting techniques. In another study, they carried out a pyrolysis experiment on a laboratory scale using simulated ASR to determine the yields of gas, oil, and char and to find out the distribution of dioxin compounds.<sup>18</sup> In the absence of polyvinyl chloride (PVC) as a source of chlorine, no PCDDs, PCDFs, or dioxin-like PCBs were found in any products of gas, oil, or char. Nourredine<sup>19</sup> has surveyed alternatives to ASR recycling techniques and concluded that as European regulations become stricter it would be better to choose recovery routes such as energy recovery in incinerators, blast furnaces, and cement kilns. One problem of blast furnaces is the nonferrous content of ASR and the rest of the products. For appropriate management, it will be necessary to reduce the formation and emission of by-product POPs during ASR thermal recycling and recovery.

### High-temperature melting

Of all the ASR recycling technologies, for which thermal recycling technologies have become the mainstream methods, increasing attention has recently been directed to gasification and melting technology. To increase the ASR recycling rate, not only thermal-recycling technology with power generation but also effective utilization of melting slag as well as metal reuse through returning fly ash into the nonferrous metal industry are important. In addition, problems related to BFRs and brominated dioxins (PBDD/DFs)

**Table 3.** Concentrations of dioxin-related compounds and brominated flame retardants in full-scale ASR melting plant

Unit	ASR	Slag	Metals	Fly ash	Exhaust gas (ng/Nm <sup>3</sup> converted at O <sub>2</sub> = 12%)		
					Combustion chamber	Gas cooler	Catalytic reactor
PCDDs/DFs <sup>a</sup> (ng/g)	0.97 (0.0043)	0.27 (0.00086)	1.1 (0.0038)	99 (1.6)	0.28 (0.0016)	–	0.15 (0.0014)
Dioxin-like-PCBs (ng/g)	30 (0.023)	0.027 (0.00023)	0.03 (0.00019)	4.6 (0.070)	0.17 (0.000019)	–	0.16 (0.000026)
PCDDs/DFs + Co-PCBs (ng-TEQ/g)	(0.027)	(0.0011)	(0.0040)	(1.7)	(0.0017)	–	(0.0014)
PBDDs/DFs <sup>b</sup> (ng/g)	30	N.D.	N.D.	0.26	0.12	N.D. (0.09) <sup>f</sup>	0.2
MoBrPCDDs/DFs <sup>c</sup> (ng/g)	N.D.	N.D.	0.03	44	N.D.	–	N.D.
Brominated diphenyl ethers <sup>d</sup> (ng/g)	310,000	0.1	0.2	2.8	2	24	N.D.
Tetrabromobisphenol A (ng/g)	15,000	0.07	0.05	0.29	14	13	28
PCBs <sup>e</sup> (ng/g)	270	0.091	0.15	22	1.5	–	2.6

Values in parentheses are WHO-TEF conversion values

MoBr, monobrominated

<sup>a</sup> 4–8 chlorinated

<sup>b</sup> 4–8 brominated

<sup>c</sup> 3–7 chlorinated

<sup>d</sup> 1–10 brominated

<sup>e</sup> 1–10 chlorinated

<sup>f</sup> Including those lower than the lower limit of determination and those higher than detection limits

contained in nonflammable plastics have also been attracting attention.<sup>20-22</sup> ASR treatment will involve evaluation of the treatment as a technology to decompose and control the formation of the by-product POPs mentioned above. Osada et al.<sup>23</sup> have carried out a test of ASR melting by using a shaft-type direct melting furnace to determine the behavior of BFRs and PBDD/DFs and the distribution of heavy metals in slag and fly ash. Table 3 shows the concentration of dioxin-related compounds and BFRs in a full-scale ASR melting plant. The exhaust gas sampled at the outlet of the combustion chamber and at the outlet of the gas cooler were found to contain few BFRs and dioxin-related compounds. The exhaust gas sampled at the outlet of the catalytic reactor contained 0.15 ng/m<sup>3</sup>N of PCDD/DFs, 0.20 ng/m<sup>3</sup>N of PBDD/DFs, and 28 ng/m<sup>3</sup>N of TBBPA (Table 3). The TEQ value derived from PCDDs/DFs and dioxin-like PCBs detected in the final emissions was 0.0014 ng TEQ/m<sup>3</sup>N. Neither MoBrPCDD/DFs nor PBDEs were detected in the exhaust gas sampled at the outlet of the catalytic reactor. The slag and metals discharged from the melting furnace contained few dioxin-related compounds or BFRs. Although the ASR contained 30 ng/g of PBDD/DFs, levels of 0.2 ng/m<sup>3</sup>N of final emission gas and 0.26 ng/g of fly ash were achieved. This is equivalent to a total release of 0.014 ng/g of ASR (a total reduction of 99.9%) with 79% of the emissions released as fly ash. No PBDD/DFs were detected in the slag or metals. The total PBDEs release was 170 ng/g of ASR, which means that 99.9999% of the input amount was decomposed, with 71% of the total released as fly ash. On the basis of these results, we can say that the DMS method is effective in the decomposition of BFRs such as PBDEs and TBBPA, as well as in the decomposition of PBDD/DFs and PCBs.

## Conclusion

The material-cycle system required by society is not a mass-consumption / mass-recycling system but a system to minimize the amount of material flow based on environment-conscious resource cycles. In the sound material-cycle society, the 3Rs (reduction, reuse, and recycling) have priority. Although recycling is the core of the material-cycle system, recycling is the lowest-priority element among the 3Rs. First of all, it is most important to reduce the consumption of resources and energy in order to minimize the environmental burden and the generation of waste. At present, we need to focus on environmental friendliness in the upstream stages, such as product design and distribution systems, and environment-conscious pre-waste material cycles in consumption behavior. An important effect of recycling systems such as the ELV Recycling Law will be the penetration of environment-conscious design into the upstream. The design for the environment (DfE) approach is being promoted to assembly manufacturers. ELV recycling initiatives should have an impact not only on recycling and recovery methods, but also on product design. On the other hand, the huge cost of forced recycling of hard-to-

recycle waste should be avoided. Recycling of materials causes degradation of their properties. Therefore, to deal with waste for which energy recovery and disposal are the only options, environmentally appropriate treatment systems should be established. Gasification and melting technology has proved effective in ASR recycling and destruction applications.

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