MATERIAL FLOW ANALYSIS OF CADMIUM APPLIED TO REVIEW MSW TREATMENT IN TAIWAN

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ABSTRACT

This study applies the material flow analysis (MFA) of Cadmium to evaluate municipal solid waste (MSW) management policy in Taiwan.

In 2002, the Cd flow in Taiwan was approximately 441.2 tons, mainly contributed by the Cd in nickel-cadmium batteries (60.15%) and plastics (33.45%). 415.6 tons of Cd entered the MSW treatment system from consumers. However, aside from the Cd emitted into the atmosphere (0.4 tons) and the Cd in incinerator ash (15.1 tons), the recycled Cd was 5.2 tons, representing a recycling rate of 1.2%. Moreover, instead of being effectively used, the recycled Cd is often casually deposited in the environment. Currently, Taiwan's Cd MFA data indicates that the MSW treatment is mainly performed by incineration, which does not conform to the main principles of sustainable development. To achieve a more sustainable policy, recycling and/or restriction of nickel-cadmium batteries and plastics turn out to be important issues.

Key Words: material flow analysis (MFA), cadmium (Cd), waste management, municipal solid waste (MSW).

I. INTRODUCTION

Taiwan implemented three six-year Taiwan Province Waste Management Programs from 1984 to 2002. Based on the landfill-oriented policy of waste management, local governments invested 52.1 billion New Taiwan Dollars (NTDs) to create 584 sanitary landfills, of which 205 are still operating. Subsequently, due to the growing popular demand for environmental quality, landfills have frequently encountered popular opposition making it more and more difficult to obtain land for creating new landfills. Based on this, the Taiwan Environmental Protection Agency (TEPA) began to implement two consecutive six-year Municipal Waste Management Programs from 1991 to 2002, making the waste treatment policy incineration-oriented. A total of 30 incinerators are eventually expected to be constructed in Taiwan. 19 incinerators have already been completed and the remainders are expected to be completed by 2007. The incineration rate of MSW exceeded 64.2% in 2002 (TEPA, 2003a). Fig. 1 details statistics on waste treatment in Taiwan from 1993 to 2002.

Cadmium (Cd) is well known as a toxic metal which is a very important metal in many applications. The Cd concentration is below 1 μg/l in natural water, below 0.05 ppm in soil, and below 0.03 μg/m^3 in the atmosphere (Wang, 2000). Acute toxicity may be caused by ingesting a high concentration of Cd in contaminated food (Hwang and Wang, 2001). High-level exposure to Cd causes damage to many organs including lungs, brain, kidneys and liver (Bonham *et al.*, 2003). Cd has been designated a carcinogen by the International Agency for Research and the US National Toxicology Program on Cancer (Waalkes, 2003). The 'Itai-Itai' disease was caused by Cd toxicity in Japan (Friberg *et al.*, 1974). This study uses the material flow analysis (MFA) of cadmium flow to evaluate municipal solid waste (MSW) management policy in Taiwan. We focus on the transformation of municipal solid waste disposal from landfill

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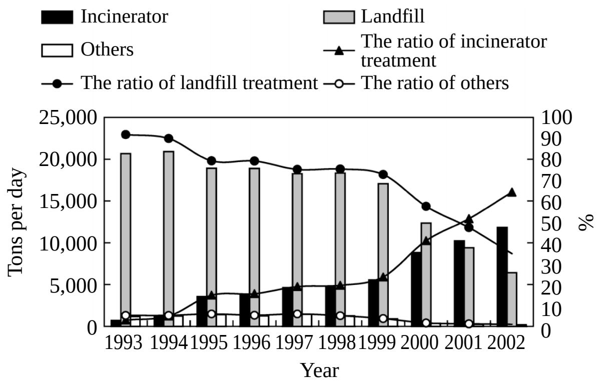

Fig. 1 Statistics map of waste treatment from 1993-2002 in Taiwan area

to incineration treatment in order to discuss the environmental impact.

II. METHODS OF MATERIAL FLOW ANALYSIS

Material Flow Analysis (MFA) is an analytical tool that provides information on the flow of goods and substances through economies and into the environment. This information can be used to develop more holistic policies for material management, including better utilization of materials and more efficient reduction of flows to the environment. This type of flow analysis has been applied to toxic heavy metals such as cadmium and lead, to valuable metals such as copper, to nutrients such as phosphorus, and to organic substances such as CFCs (Baccini and Brunner, 1991). The MFA method is essentially a materials balance for an element or compounds in the anthrop sphere (the physical industrial economy) of a particular region. This method includes a balance of appropriate goods at the enterprise level, including the waste management system.

This method can be used to examine the current and future anthropogenic flows of the element through the incinerator. Various material management strategies can be designed and tested using MFA to compare the flow to the environment, or to compare acceptance criteria for environmental loading. A main advantage of the MFA method is that it accounts for stocks of the mentioned heavy metals in an incinerator, and can be used to forecast future flows into the environment under various materials management scenarios.

III. MFA OF Cd IN TAIWAN

According to import and export data from Taiwan Customs in 2002, the Cd flow into the Taiwan environment was around 441.2 tons, including 265.4 tons in Ni-Cd batteries, 250.4 tons in plastics, 11.6 tons in lead/zinc, 5.3 tons in limestone, 5.2 tons in coal, 4.8 tons in iron and steel, 0.5 tons in gypsum and 0.3 tons in phosphorus-containing fertilizer. The MFA of Cd in detail is shown in Table 1.

The total amount of municipal solid waste in Taiwan was 6,723,665 tons in 2002. 64.2% of garbage was treated by incineration, 34.8% by landfill, and 1% by compost. Plastic recycling amounted to 47,967 tons, and recycled Ni-Cd batteries totaled 29.9 tons (5.2 tons Cd was recycled). The incinerator ash is composed of fly ash and bottom ash. The average amount of the heavy metal Cd content in fly ash is 773 ppm, while the Cd content in the bottom ash is 178 ppm (TEPA, 2003b). The above values were used to calculate the Cd in ash produced by the incinerators in 2002. The Cd in fly ash contributed 50.96% of the total amount of Cd in ash, while the bottom ash contributed 48.91%, and the airborne emissions contributed 0.14%. The obtained Cd metal content of the ash in incinerators in Taiwan in 2002 was 266.1 tons, compared to 144.3 tons for landfills and 0.4 tons for airborne emissions.

In the case of the soluble Cd of the ash in incinerators, the average soluble Cd of fly ash in the incinerators is 4.25 mg/l, and the bottom ash is 0.01 mg/l from the TCLP (Toxicity characteristic leaching procedure) testing (Wang and Chiang, 1996). Putting the above values into the 2002 ash amount of the incinerators, the soluble Cd metal of the fly ash was 14.9 tons and that of the bottom ash was 0.2 tons, totaling 15.1 tons. The Cd flows in the MSW treatment in Taiwan are shown in Table 2 and Fig. 2.

IV. DISCUSSION OF CADMIUM CONTENT IN DOMESTIC AND FOREIGN WASTE

PVC plastics use Cd compounds as plastic stabilizers. Plastics such as ABS, HDPE, LDPE, PS, and PP employ pigments containing Cd. Furthermore, because Taiwan has been the kingdom of plastics, the Cd content in solid waste is rather high. Plastics took up 22% of municipal solid waste in 2000 in Taiwan, averaging far higher than the OECD countries, and doubling the 11% recorded for the United States (OECD, 2000).

The percentage of plastic elements is high and the Cd recycling rate is a mere 1.2% of total Cd flow. The Cd content in solid waste is quite high, even after the incineration of solid waste. The Cd in both fly and bottom ash is significantly higher than in America, Japan, Germany, Sweden, Switzerland and other developed nations. The Cd content in garbage was 61.65 ppm in Taiwan, higher than the 20 ppm in American garbage investigated by the American Environmental Protection Agency in 1987(USEPA, 1987).

Table 1 Cd flow in Taiwan 2002

		Item / sub-item	(1) Imported amount of each item / sub-item (tons)	(2) Exported amount of each item / sub-item (tons)	(3) Mining / extraction amount of each item / sub-item (tons)	(4) The percentage of Cd of each item /sub-item (%)	(5) The amount of Cd of each item /sub-item[a] (tons)
Material		Plastic stabilizer	248.0	0	0	87.5%[b]	217.0
		Plastic pigments	49.5	3.2	0	72.2%[c]	33.4
	Pb-Zn	Pb	41.0	0	0	0.1%[d]	11.6
		Zn ores	0	87.0	0	0.2%[d]	11.6
		Zn residues	10,729.0	4,644.0	0	0.01%[d]	11.6
		Others	362,297.6	138,219.0	0	0.005%[d]	11.6
	Limestone		1,640,678.0	821.0	3,677,000.0	0.0001%[e]	5.3
		Coal	51,679,469.0	12,685.0	0	0.00001%[d]	5.2
	Steel/iron	Iron	15,268,052.6	30,127.6	0	0.00002%[d]	4.8
		Steel residues	5,278,826.0	292,403.0	3,000,000.0	0.00002%[d]	4.8
		Steel products	292,403.0	57,257.0	10,000,000.0	0.000001%[d]	4.8
		Gypsum	488,560.2	7481.3	0	0.0001%[f]	0.5
	Copper	Cu ores	7	20	0	0.06%[g]	0.3
		Cu residues	18,539	766		0 0.001%[h]	0.3
		Refined Cu	710,969.2	216,634.9	0	0.00003%[i]	0.3
	Phosphate Fertilizers	Phosphate fertilizers	201,224.1	237.2	0	0.00015%[j]	0.3
		Compound fertilizers	24,703.0	40.0	0	0.00015%[j]	
Production		Ni-Cd batteries	1968.6	199.5	0	15%[k]	265.4
		PVC plastic	89,005.0	665,033.0	1,470,356.0	0.0147%[l]	-85.0[m]
		Other plastic	581,024.0	2,520,499.0	3,679,437.0	0.00091%[l]	-17.6[m]
Total							441.2

[a] Cadmium total amount = (imported amount-exported amount + domestic output) × cadmium per unit.
[b] This study presumed the plastic stabilizer was in form of cadmium oxide (CdO) compound. Consequently, the percentage of cadmium of CdO is 87.5%
[c] from (Tamaddon and Hogland, 1993);
[d] from (Kwonpongsagoon *et al*., 2002);
[e] from (Mantell, 1975) ;
[f] from (Senn and Milham, 2000);
[g] from WMC Resource Ltd. http://www.wmc.com.au/);
[h] from (Stigliani and Anderberg, 1994);
[i] from (Woodcock and Hamilton, 1993)
[j] The TEPA standard of cadmium is 1.5 mg/kg
[k] from (Bundesamt, 1997)
[l] from (TEPA, 2002)
[m] The exported amount of cadmium is larger than the imported amount of cadmium in Taiwan

The Cadmium could release into the environment after incineration. 95% of the Cd was distributed in the fly ash and bottom ash , and 5% was emitted into the air (Vogg, 1986). A similar study by Dieter on an incineration factory also indicated that 10% of the Cd may be distributed in the bottom ash, 85% in the fly ash, 3% in the waste water and 2% in the air as emissions (Dieter, 1989).

Table 2 The Cd flows in the MSW treatment in Taiwan 2002

Waste treatment alternatives	Treatment amount[a] (tons)	Amount of ash[a] (tons)		Amount of cadmium (tons)		Amount of soluble/insoluble cadmium in ash (tons)	
Incineration	4,316,125.0	(1) + (2) = 905,675.0	(1) Fly ash = 175,634.0 (2) Bottom ash = 730,041.0	(3) + (4) + (5) = 266.1[b]	(3) Fly ash = 135.7 (4) Bottom ash = 130.0 (5) Flue gas = 0.4	Soluble Insoluble Soluble Insoluble --	(6) 14.9[e] (7) 120.8[e] (8) 0.2[e] (9) 129.8[e]
Landfill	2,340,745.0	--		144.3[c]		--	
Compost	66,795.0	--		0[d]		--	
Recycling	(10) PVC plastics = 2377.2 (11) Other plastics = 45,590.5 (12) Ni-Cd batteries = 29.9	--		(13) + (14) + (15) = 5.2[f]	(13) PVC plastics = 0.3 (14) Other plastics = 0.4 (15) Ni-Cd batteries = 4.5	--	
Sum	6,771,662.6	905,675.0		415.6		--	

[a] from(TEPA, 2003a)

[b] (3) = (1) $\times$ (mg of cadmium in unit kilogram of fly ash: 773 mg/Kg, from (TEPA, 2003b)) $\times 10^{-6}$; (4) = (2) $\times$ (mg of cadmium in unit kilogram of bottom ash: 178 mg/Kg, from (TEPA, 2003b)) $\times 10^{-6}$; (5) = (3) $\times$ 50.96% $\div$ 0.14%, from (TEPA, 2003b)

[c] Cadmium amount in landfills = Treatment amount of landfill $\times$ (mg of cadmium in unit kilogram of treatment amount of landfill: 61.65 mg/kg, from (TEPA, 2003b)) $\times 10^{-9}$

[d] The garbage in compost does not contain plastics and nickel-cadmium batteries. Consequently, the cadmium in this category was presumed to be zero

[e] (6) = (3) $\times$ 2(liters) $\times$ (The TCLP soluble cadmium of the fly ash: 4.25 mg/L, from (Wang and Chiang, 1996)) $\div$ 100 (gram) $\times 10^{-5}$; (7) = (3) – (6); (8) = (4)$\times$ 2 (liters) $\times$ (The TCLP soluble cadmium of the bottom ash: 0.01 mg/L, from (Wang and Chiang, 1996)) $\div$ 100 (gram) $\times 10^{-5}$; (9) = (4) – (8)

[f] (13) = (10) $\times$ 0.0147%, from (TEPA, 2002); (14) = (11) $\times$ 0.00091%, from (TEPA, 2002); (15) = (12) $\times$ 15%, from (Bundesamt, 1997)

V. ASSESSMENT OF MSW DISPOSAL AND RECYCLING POLICY

The materials can be divided into four major categories based on their decomposition and toxicity: Degradable/Not Toxic, Persistent/Not Toxic, Degradable/Toxic, and Persistent/Toxic. Cadmium belongs to the persistent and toxic, being difficult to decompose, poisonous, and having accumulative toxicity (Geiser, 2001). Therefore, the detoxification of Cd should be the important issue.

1. Detoxification Assessment of MSW Landfill Treatment

Cadmium is retailed stably in production Ni-Cd batteries, PVC plastics, and other plastics, or is buried in a landfill after being discarded. Therefore, cadmium flow will not leach out easily and cause environmental contamination problems.

Table 3 proves this hypothesis: after being used 30 years, Taiwan's Landfills fit the environmental standard on the concentration of Cd in ground water and soil (BEPH, 1999).

2. Detoxification Assessment of MSW Incineration Treatment

The risk of Cd release into the environment may happen through the fly and bottom ash of incineration. This study discovered that the Cd released into the environment was 0.4 tons in the atmosphere, 265.7 tons in the form of ash (fly and bottom ash) and 15.1 tons of soluble Cd. The actual monitoring data of Taiwan's EPA, the hourly stack release amount of Cd of the Shulin Incinerator was 0.000230 kg/hr and the

Table 3 Cadmium in the groundwater and soil of landfills

	Cadmium concentration in the soil (mg/kg)	Cadmium concentration in the underground water	Notes
Nanliao Landfill	ND-1.7 (average 1.09)	ND	Nanliao Landfill was opened in June 1973, closed in November 1994.
Chinshui Landfill	ND-1.9 (average 0.51)	ND	Chinshui Landfill was opened in December 1994, still in use today.
Heavy metal content in farmland surface soil in Taiwan	0.05-2.65	–	TEPA, 2000a

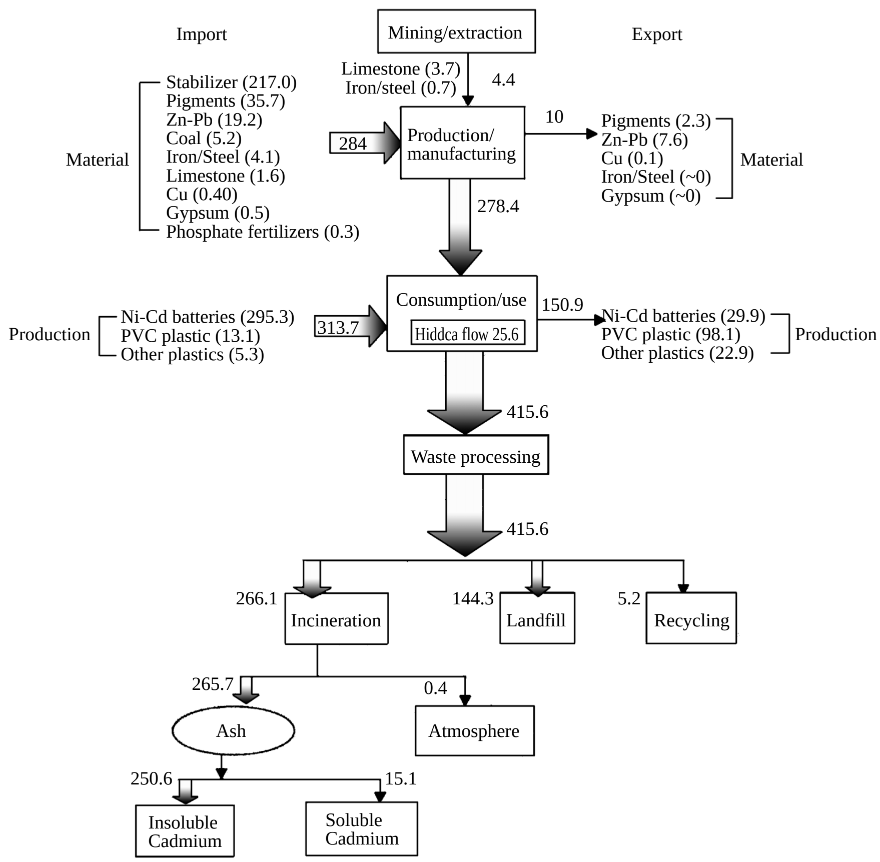

Fig. 2 Cadmium material flows in Taiwan 2002. (Unit: tons)

annual release amount of Cd was 2.0148 kg/year (TEPA, 2000b).

Simulating the ISCST3 (Industrial Source Complex Short Term Model, version 3) Modelair pollution model by using the waste gas release amount of the pollutants in the flue of the Shu-Lin Incinerator, the concentration of pollutants from the incinerator is found to be highest within a three kilometer radius, with the direction of highest pollution concentration being almost identical to the supplementary wind direction.

If the emission rate of 0.000230 kg/hr is used for simulation, the maximum emission of Cd from Shu-Lin Incinerator is 1.60 mg/m^2, and the maximum annual deposition per hectare is 16 g. From the simulating results, we notice that the emission of Cd in particular areas attracts our attention. Table 4 and Fig. 3 show the results of Cd deposition from Shu-Lin Incinerators.

Furthermore, if we assume that the topsoil depth at a pollution site contaminated by Cd is 15 cm and on the basis of the concentration standard level of Cd

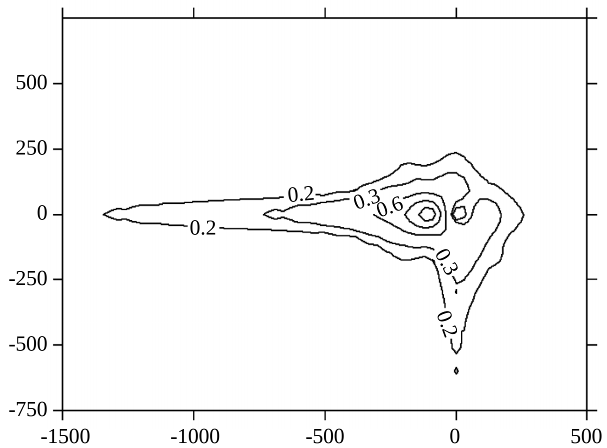

Fig. 3 ISCST3 Simulation of the Granule Sedimentation State of the Release from the Shu-Lin Incinerator (Unit: g/m^2)

in soil (5 mg/kg), then one hectare of polluted soil will hold approximately 19.5 kg (the amount of Cd in soil = Cd concentration in soil × soil gravity × soil volume, 19.5 kg = 5 mg/kg × 2.6 Mg/m^3 × 15 cm × 10000 m^2) Cd. Therefore, if we emit 2.0148 kg/year Cd from an incinerator stack to the nearby area, then it will become polluted to that level (19.5 kg) in a period of time.

3. Recycling Assessment of MSW Treatment

This study estimated that the municipal solid waste recovery of Cd in 2002 was merely 5.2 tons, which is 1.2% of the total Cd amount. This Cd material flow in Taiwan presently does not conform to the principles of sustainable development. To achieve a more sustainable policy, recycling of nickel-cadmium batteries and plastics turn out to be important issues. Moreover, the recovered Cd was even not reused, but mostly deposited in the environment. Studies of recycling and reuse technology should be developed in the future.

Viewed from the perspective of Cd material flow in Taiwan, the damage the Cd may cause to the environment involves the Cd containing particle released from stacks during incineration, and also the fly and bottom ash containing a high concentration of Cd. Therefore, the main goal is to develop methods of recycling and reuse of the Cd in the ash.

Although MSW treatment policy in Taiwan is currently dominated by incineration, Taiwan continues to lack a single sanitary landfill to treat ash with a high Cd concentration. Most fly ash was treated by using solidification and then was handled together with other municipal solid waste. Based on the material flow of Cd, it was still possible to release Cd into the environment.

Table 4 Simulating results of deposition of Shu-Lin Incinerator

Interval (m)	Deposition (mg/m^2)	0~0.1	0.1~0.2	0.2~0.4	> 0.4
100	Area (hectare)	3567	118	28	8
	Average deposition (mg/m^2)	0.02	0.13	0.27	0.70
	Total deposition (g/yr)	804.27	150.40	76.38	56.12

VI. CONCLUSIONS

By using two parameters, namely resource recycling and detoxification, and the method of Cd flow in MSW, this study analyzes the problem of transforming MSW disposal strategy from the past, sanitary landfills, to incineration treatment. Applying MFA of Cd in replacing landfill with incineration for MSW treatment is a practicable method. This study shows that the Cd in Taiwanese municipal solid waste reaches up to 61.65 ppm. Viewed from the perspective of Cd material flow, the present MSW treatment policy in Taiwan, which is mainly based on replacing landfill with incineration, does not conform to the principles of sustainable development. That is, the policy does not conform with recycling and detoxification principles, with its rather low recycling of plastics and Ni-Cd batteries. To reduce Cd release from incinerators, recycling of plastics and Ni-Cd batteries must urgently be promoted, to reduce Cd levels in MSW and solve problems of Cd pollution that may be caused by incineration. Although the waste gas released from incinerators conforms to the government emission standards, it is still possible for this waste gas to harm humans and the environment. Consequently, the government emission standards of Taiwan still need to be further researched.

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