METALS IN MSW — WHERE ARE THEY AND WHERE DO THEY GO IN AN INCINERATOR?

H. GREGOR RIGO
Rigo & Rigo Associates, Inc.,
Berea, Ohio

A. JOHN CHANDLER
A. J. Chandler & Associates Ltd.,
Willowdale, Ontario, Canada

ABSTRACT

The source and fate of metals entering and leaving a modern municipal waste combustor [MWC] were identified during The WASTE Program's Burnaby, B.C. field exercise in June 1991. The solid waste feed was sorted, screened and the trace metals analyzed and the residue and stack emissions simultaneously characterized at the 240 tonne per day Greater Vancouver Regional District [GVRD] incinerator. The waste characterization reveals that many environmentally significant metals are constituents of natural waste components and are not necessarily introduced during manufacturing processes. The partitioning of metals throughout the incineration and air pollution control [APC] systems was also determined. This discussion focuses on mercury due to current interest in the metal. The performance of supplemental mercury control systems is assessed and a theoretically based activated carbon mercury control system performance model is presented.

INTRODUCTION

The popular press has raised the general public's awareness of the damage potential of inappropriate environmental releases of trace metals. Pressure to ban certain solid waste management methods and increase the regulation of systems that get built has frequently resulted. Cost or pressure for immediate action commonly preclude the work necessary to establish scientifically sound public policy. Unfortunately, regulations that are not based upon detailed investigation of the alternatives starting with demonstratably valid data and assumptions run the risk of doing net environmental harm.

The characterization of the entire municipal solid waste [MSW] stream and the behavior of specific components in management systems is a case in point. Prior to initiation of The WASTE [Waste Analysis, Sampling, Testing and Evaluation] Program's Burnaby field exercise, the last major series of MSW composition studies were completed in the mid-1970s in the United States and Canada. Since then, updates have been based largely upon the methodology developed by Franklin Associates Ltd. that tracks industrial metal usage and consumer patterns to estimate the changing nature of the waste stream. This material balance approach is clearly valid for identifying waste components that are potentially amenable to pollution prevention initiatives, but does not provide a basis for identifying whether such actions are likely to result in a measurable environmental improvement. Unless the natural background and a combination of low metal content components can be safely ignored, intervention to reduce industrial usage, hence discards, can result in the expenditure of large sums of money with little environmental benefit.

This paper presents some of the results from The WASTE Program's first project — the simultaneous characterization of the inlet and outlet flow streams for MWC No. 1 at the Greater Vancouver Regional District [GVRD] incinerator facility in Burnaby, B.C. (WASTE, 1993). This nominal 10 tonne/hr B&W steam generator is equipped with a Martin grate and combustion control system, and a Flakt humidification, dry lime injection and pulse jet fabric filter air pollution control system. A sodium sulfide mercury control system was employed at the time of the test. Incinerator operating and continuous emissions monitoring data were collected before, throughout, and after the test period. Simultaneous sampling of waste, residues, boiler outlet gas concentrations and stack emissions for a

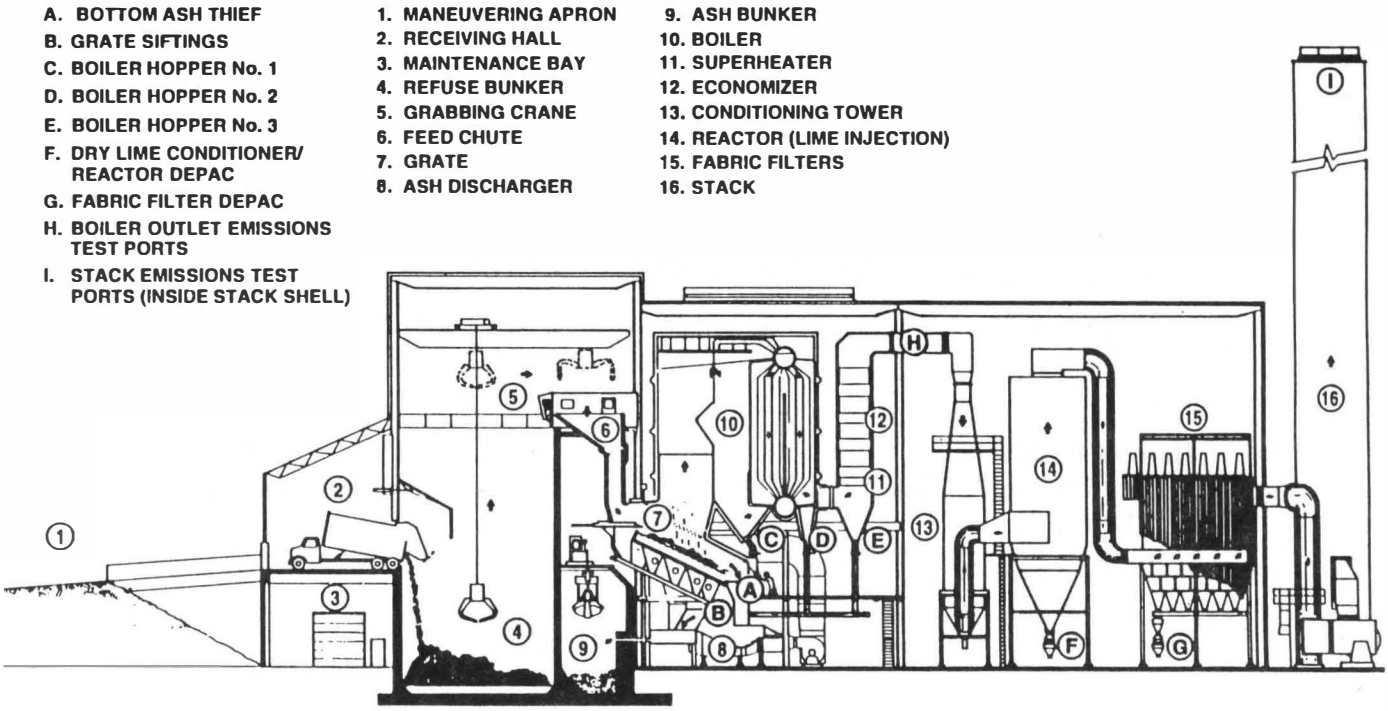

FIG. 1 PLANT SCHEMATIC SHOWING MAJOR EQUIPMENT AND SAMPLING LOCATIONS

number of metals was carried out at the locations identified in Figure 1 using standard procedures. A total of ten 4-hour runs were conducted the last week of June, 1991 with complete data being collected for the first nine runs. A plant upset just before Run 10 prevented waste sorting during that run.

The municipal solid waste [MSW] delivered to the GVRD Burnaby incinerator generally comes from the eastern suburbs of Vancouver, B.C. The communities are moderately affluent with typical suburban population density in the developed areas. Heavy ocean shipping-related industries are found along the waterways and a rapidly growing software industry is located inland. Extensive blue-box curbside recycling programs and beverage bottle deposit laws characterize the area's recycling and waste reduction efforts. The blue-box program recovers newsprint, metal and glass containers with additional materials being recovered in specific communities. Based on regional beverage container deposit in formation, it appears that bottle recovery rates are influenced by both the amount of the deposit and convenience. High recovery rates are achieved for bottles that come with easy-return cartons (six packs of beer bottles) or bottles that are relatively large and thus easier to handle (HDPE milk jugs and 1 and 2 litre PETE soda bottles). Lower recovery rates are shown for cans which may be sold individually and, if packaged, must be accumulated before they can be placed back into their original shipping carton.

METAL PARTITIONING BETWEEN MSW COMPONENTS

Procedure

Nearly 2.23 tonnes (2.46 tons) of MSW were sorted into the 168 sort categories shown in Table 1. These categories were developed to provide information needed to support planning recycling efforts, identify materials that The WASTE Program's literature search indicated might be significant sources of trace metals and eliminate the need to open sealed plastic, glass or metal containers.

To obtain samples from the pit, the crane operator took a light grapple load (one third to one half full) of waste, opened the grapple over a half yard motorized construction wheelbarrow located beside the incinerator's feed chute. Spilled MSW was removed from around the wheelbarrow and charged into the incinerator. The full wheelbarrow was then taken into a clean air pressurized 10 mil plastic sheeting enclosure in the bunker building where sorting was performed by a supervisor and five sorters.

The material in the wheelbarrow was put on a 2 in. (50 mm) opening steel screen supported on saw horses. Bags and boxes were opened on this sorting table and the less than 2 in. (50 mm) fraction fell through to the plastic sheet-covered floor below. The material retained on the sorting table was separated into labeled containers. Next, the −2 in. (−50 mm) material under the sorting table was separated on a $\frac{1}{2}$ in. (12.5 mm) screen to remove the fines.

TABLE 1 LIST OF SORTING CATEGORIES USED FOR WASTE SAMPLING AT BURNABY

MSW GROUP	MAJOR CATEGORY	MINOR CATEGORY	SUB 1
PAPER	FINE/COMPUTER/OFFICE		
	BOOKS		
	MAGAZINES	GLUED	
		NOT GLUED	
	LAMINATES	WAX/PLASTIC	
		FOIL	
	NEWSPRINT	GLUED	
		NOT GLUED	B&W
			COLOUR
	BROWNS	CORRUGATE	
		KRAFT	
		BOX BOARD	
	RESIDUAL MIXED		
PLASTIC	FILM	COLOUR	
		FLEXIBLE	
		RIGID	
	BEVERAGE	1 (PETE)	
		2 (HDPE)	
		7 (OTHER)	
		NONIDENTIFIED	
	FOOD	1 (PETE)	
		2 (HDPE)	
		3 (PVC)	
		4 (LDPE)	
		5 (PP)	
		6 (PS)	
		7 (OTHER)	
		NONIDENTIFIED	
	HOUSEHOLD	1 (PETE)	
		2 (HDPE)	
		3 (PVC)	
		4 (LDPE)	
		5 (PP)	
		6 (PS)	
		7 (OTHER)	
		NONIDENTIFIED	
	HOUSEWARES	CLEAR	
		WHITE	
		BLUE	
		YELLOW	
		OTHER	
	TOYS AND OTHER		
	VIDEO TAPES AND FILM		
ORGANICS	YARD & GARDEN	LAWN/PLANTS	
		BRANCHES	
	FOOD WASTE	ORGANIC	
		SHELLS AND BONE	
	WOOD	FINISHED	
		UNFINISHED	
	TEXTILES		
	LEATHER		
	RUBBER		
	FOOTWEAR		
	OTHER		
METALS	FERROUS	BEER	
		SOFT DRINK	
		FOOD	

MSW GROUP	MAJOR CATEGORY	MINOR CATEGORY	SUB 1
METALS (Cont'd)	FERROUS (Cont'd)	BAND & STRAPS	
		MANUFACTURED	
	BIMETALLIC	BEER	
		SOFT DRINK	
		FOOD	
		ELECTRIC MOTORS	
		OTHER	
	NON-FERROUS	BEER	
		SOFT DRINK	
		FOOD	
		MANUFACTURED	
		FOIL/PACKAGING	
		OTHER	
GLASS	BEER	CLEAR	
		GREEN	
		BROWN	
		OTHER COLOUR	
	SOFT DRINK	CLEAR	
		GREEN	
		BROWN	
		OTHER COLOUR	
	LIQUOR	CLEAR	
		GREEN	
		BROWN	
		OTHER COLOUR	
	WINE	CLEAR	
		GREEN	
		BROWN	
		OTHER COLOUR	
	FOOD	CLEAR	
		GREEN	
		BROWN	
		OTHER COLOUR	
	OTHER GLASS	CLEAR	
		GREEN	
		BROWN	
		OTHER COLOUR	
	LIGHT BULBS		
	FLUORESCENT TUBES		
INORGANIC	LIGHT CONSTRUCTION	ROCK/SAND/DIRT	
		CONCRETE	
		CERAMICS	
		DRYWALL/PLASTER	
		INSULATION	FGLASS
			OTHER
	OTHER		
OVERSIZE/ BULKY	WHITE GOODS		
	FURNITURE		
	TRANSPORT PARTS		
	OTHER		
SMALL APPLIANCES	BRASS/METAL		
	ELECTRICAL PARTS	PLASTIC	
		METALS	
HOUSEHOLD HAZARDOUS	BATTERIES	LEAD ACID	
		BUTTON	
		CARBON	
		NI-CAD	

MSW GROUP	MAJOR CATEGORY	MINOR CATEGORY	SUB 1
HOUSEHOLD HAZ (Cont'd)	BATTERIES (Cont'd)	ALKALINE	
		OTHER	
	MEDICAL/ BIOLOGICAL	DIAPERS	
		BANDAGES	
		NEEDLES & SHARPS	
		LATEX	
		HYGIENE PRODUCTS	
		ANIMAL BEDDING/LITTER	
		CARCASS	
		OTHER	
HAZARDOUS W/ CONTAINER	STAINS & PRESERVES	PLASTIC	
		METAL	
		GLASS	
		OTHER	
	LATEX PAINT	PLASTIC	
		METAL	
		GLASS	
		OTHER	
	OIL BASED PAINT	PLASTIC	
		METAL	
		GLASS	
		OTHER	
	UNKNOWN PAINT	PLASTIC	
		METAL	
		GLASS	
		OTHER	
	SOLVENTS	PLASTIC	
		METAL	
		GLASS	
		OTHER	
	CLEANER	PLASTIC	
		METAL	
		GLASS	
		OTHER	
	SOAPS & DETERGENTS	PLASTIC	
		METAL	
		GLASS	
		OTHER	
	OIL	PLASTIC	
		METAL	
		GLASS	
		OTHER	
	LIQUID PESTICIDE/ HERBICIDE	PLASTIC	
		METAL	
		GLASS	
		OTHER	
	SOLID PESTICIDE/ HERBICIDE	PLASTIC	
		METAL	
		GLASS	
		OTHER	
	OTHER	PLASTIC	
		METAL	
		GLASS	
FINES			

The retainage was sorted into the labeled containers. Once the point of diminishing returns was reached, the remaining $>\frac{1}{2}$ in. (>12.5 mm) material was visually proportioned among the predominant categories (e.g. 50% mixed paper, 25% leaves and grass and 25% plastic film).

At the end of each sort, the separated material was weighed, dried at 140°F (60°C) for at least 24 hours and reweighed to both determine the air-dried moisture content and stabilize the sample. The size consist of selected samples was determined and the screen cuts were recombined to form fines ($<\frac{1}{2}$ in. or <12.5 mm), middlings ($\frac{1}{2}$–4 in.; 12.5–100 mm) and overs (>4 in. or >100 mm) fractions of component samples destined for the laboratory. The recombined samples were then shredded in an unmodified 5 HP hammer mill type garden mulcher to produce a nominal $<\frac{1}{2}$ in. (12.5 mm) material which was subsampled using cone and quarter techniques to yield representative final field samples.

Although the final field samples sent to the laboratory were generally less than $\frac{1}{2}$ in. (12.5 mm) in size, further size reduction to pass a No. 18 (1 mm) screen was necessary before they could be digested and analyzed. A Wiley mill was used to fine grind most samples. Dry ice was used to embrittle flexible plastics which facilitated milling. Metals were formed into solid plugs and drilled without the aid of lubricant to produce the swarf used as the laboratory sample. Glass and other mostly in organic composite materials were processed in a jaw crusher and agate mill. Portions of some of the composites accumulated in the agate mill; these were passed through the Wiley mill and recombined with the rest of the parent sample prior to analysis.

The samples were digested using microwave techniques similar to proposed SW-846 Method 3051 (EPA, 1992), but with sequential aqua regia and hydrofluoric acid digestion steps added as necessary to achieve total dissolution of organic and silicate matrices. Direct coupled ion plasma techniques were used to analyze: aluminum, arsenic, boron, barium, cadmium, chromium, copper, iron, mercury, manganese, nickel, lead, antimony, selenium, tin and zinc. These are the metals generally listed in North Ameri can and European regulations. Thallium was not included since detectable levels have not been found in North American MSW incinerator emissions or residues and industrial usage is restricted to certain types of specialized, low temperature conductors.

General Sort Results

Table 2 is a summary of the median composition of the 31 sorted solid waste samples and elemental content of each component. In Figure 2, the observed composition range, median and upper and lower 95% confidence limits for aggregated waste categories are displayed.

TABLE 2 MEDIAN FRACTIONS AND METAL CONCENTRATIONS FOR INDIVIDUAL WASTE COMPONENTS

Group	Major Category	Minor Category	Sub Category	Median % Component	ELEMENTAL COMPOSITION IN PPM (g/TONNE OF COMPONENT)															
					Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Sb	Se	Sn	Zn
paper	fine/computer/office			2.09	3,283	1.3	2.2	7.7	0.1	0.1	3.4	8	806	0.3	24.6	7.9	4.5	2.3	0.25	8	208
	books			0.24	2,874	0.4	37.6	62.6	0.01	0.4	8.7	40	399	0.2	48.2	1.4	0.005	0.03	0.13	24	88
	magazines	glued		0.88	9,808	1.1	2.5	24.2	7.4	0.001	16.6	26	771	0.3	50.9	17.6	0.4	1.6	0.08	36	36
		not glued		0.93	22,413	1.8	7.6	36.9	0.2	0.3	5.8	37	4,133	0.3	50.9	8.2	5.9	98.9	0.13	31	18
	laminates	wax/plastic		1.66	5,603	0.7	3.7	22.3	0.1	0.3	3.2	7	1,230	0.1	25.5	5.4	7.1	3.7	0.05	12	16
		foil		0.30	101,262	0.8	15.4	25.1	7.2	0.1	44.6	226	2,049	0.1	64.5	8.7	92.3	20.2	0.02	11	119
	newsprint	glued		0.29	3,772	0.8	6.1	9.3	0.3	0.1	1.3	10	327	0.3	19.5	4.3	2.4	1.2	0.11	18	8
		not glued	b&w	4.55	4,203	0.7	6.9	18.4	1.0	0.1	3.8	13	661	2.9	45.0	6.2	7.2	2.5	0.11	24	19
			colour	1.32	4,282	0.6	16.5	23.2	6.3	0.1	215.1	36	1,396	0.3	81.9	106.5	5.7	1.8	0.07	25	29
	browns	corrugate		9.19	1,030	0.6	3.1	6.3	0.3	0.1	1.6	3	338	0.1	17.3	3.8	3.8	1.5	0.04	4	10
		kraft		1.86	1,687	0.8	4.7	11.3	1.0	0.1	4.7	11	825	0.5	28.1	7.7	9.3	1.6	0.05	13	22
		box board		1.68	3,319	0.7	6.0	31.0	1.1	0.2	5.4	12	869	0.2	41.0	6.8	12.0	2.8	0.04	11	29
	residual mixed			13.52	1,505	1.2	6.6	14.3	0.1	1.7	33.0	24	1,500	0.4	51.2	7.5	229.4	5.0	0.03	25	81
plastic	film	colour		3.13	3,236	0.5	13.7	169.8	0.1	6.6	115.1	25	1,157	0.2	34.1	8.0	361.5	27.2	0.01	92	1,132
		flexible		2.51	980	0.7	29.7	11.0	0.1	2.8	86.0	20	1,059	0.2	33.0	5.9	279.3	10.7	0.02	31	67
		rigid		0.30	12,451	0.3	5.4	128.5	0.1	37.2	119.6	75	848	0.1	53.0	27.2	33.7	17.1	0.04	179	52
	food/ beverage/ household	1 (pete)		0.015	1,394	0.8	193.5	8.0	1.9	5.3	16.7	31	1,927	0.2	60.0	8.3	61.5	174.1	0.05	6	97
		2 (hdpe)		0.182	2,438	0.5	29.4	83.5	2.7	2.9	15.0	24	1,240	0.2	36.5	7.0	60.6	52.0	0.05	14	142
		3 (pvc)		0.001	90	0.0	7.2	0.0	0.02	4.5	2.6	2	216	0.1	11.7	2.6	2,160	29,700	0.005	17	3
		4 (ldpe)		0.001	262	0.2	12.0	5.0	4.0	2.5	4.7	10	129	0.1	9.4	4.2	56.0	16.0	0.03	0.01	89
		5 (pp)		0.026	736	0.5	5.3	4.5	0.04	1.9	31.6	16	1,064	0.1	31.9	6.0	69.3	51.2	0.03	18	40
		6 (ps)		0.006	36	0.2	3.9	3.4	0.03	4.7	7.1	9	170	0.1	3.6	5.7	25.0	44.0	0.02	25	98
		nonidentified		0.684	19,688	1.2	20.0	117.9	0.5	79.3	44.1	57	2,457	0.4	41.7	38.2	157.7	101.3	0.15	96	273
	housewares	clear		0.064	406	0.1	0.5	18.5	0.5	0.9	6.4	7	298	0.1	6.1	15.6	61.7	24.3	0.02	316	108
		white		0.262	856	0.2	7.1	8.5	1.5	2.5	595.2	44	9,056	0.2	249.5	146.4	41.8	24.9	0.02	66	129
		blue		0.039	1,686	3.1	16.9	565.0	0.03	289.7	8.7	80	251	0.1	11.2	16.3	64.3	90.3	0.03	106	76
		yellow		0.049	826	0.3	8.1	227.1	0.1	104.8	1,287	17	921	0.1	22.7	9.0	2,479	62.9	0.08	145	277
		other		0.663	1,154	0.3	5.9	168.1	0.5	100.9	359.3	29	634	0.3	14.1	2.8	647.3	254.7	0.22	62	199
	toys and other			0.257	565	0.5	9.5	83.1	1.5	75.8	229.1	98	26,049	0.1	219.5	27.7	102.8	93.4	0.03	66	349
	video tape/film			0.001	136	14.3	64.7	27.4	0.0	2,195	94.1	38	176,400	0.2	338.1	17.6	882.0	211.7	0.02	60	774
organics	yard & garden	lawn & plant		10.87	15,547	7.3	527.1	132.8	2.6	6.0	101.3	690	16,064	1.4	498.4	23.6	153.6	52.2	0.07	79	365
		branches		2.46	4,328	0.9	22.5	54.2	9.7	1.1	24.1	45	4,082	0.4	184.7	10.8	61.9	7.8	0.04	19	124
	food waste	organic		3.32	2,910	1.2	328.7	17.4	0.0	2.0	22.6	43	3,164	0.3	101.2	4.8	72.0	12.8	0.05	38	186
		shells & bone		3.44																	
	wood	finished		3.29	431	5.1	14.6	46.3	16.1	1.1	113.0	109	36,397	0.2	258.3	8.3	562.9	0.2	0.02	18	117
		unfinished		6.06	415	34.0	20.9	27.9	17.4	0.04	58.1	46	718	0.4	117.2	0.8	324.3	0.5	0.01	31	205
	textiles			4.40	894	0.4	6.9	23.0	2.2	2.8	440.1	67	1,265	1.1	36.7	0.8	128.2	96.4	0.03	43	142
	leather			0																	
	rubber			0.10																	
	footwear			0.65	2,648	0.7	5.6	91.9	2.7	11.9	1,831	25	649	0.1	25.2	5.5	133.8	4.0	0.03	37	764
	other			0.28																	
metals	ferrous	beer cans		0.015	120,400	8.8	125.6	43.0	0.004	61.9	302.7	323	35,260	36.4	4,690	166.0	230.5	68.8	0.06	986	886
		soft drink cans		0.012	120,400	8.8	125.6	43.0	0.004	61.9	302.7	323	35,260	36.4	4,690	166.0	230.5	68.8	0.06	986	886
		food cans		1.26	1,348	7.0	161.0	1.7	0.004	43.1	188.8	99	43,216	5.6	3,459	160.4	344.3	88.2	0.04	793	1,566
		band & strap		0.06	626	40.0	372.0	2.2	0.1	15.0	492.0	119	820,000	0.02	14,000	41.7	596.0	163.0	0.09	216	30
		manufactured		2.17																	
metals (cont'd)	bimetallic	beer cans		0																	
		soft drink cans		0.001																	
		food cans		0.077																	
		electric motor		0.002	181,300	9,480	98.0	1,274	0.0	9.1	289.1	744,800	166,600	5.4	1,056	38.9	609.6	74.5	20.58	137	7,332
		other		0.015																	
	non-ferrous	beer cans		0.058	750,000	0.2	9.0	67.0	0.01	3.0	95.0	1,141	3,412	0.3	7,694	27.9	68.0	20.0	0.01	80	170
		soft drink cans		0.182	585,583	0.4	19.7	157.7	0.3	6.0	89.3	1,094	4,108	0.4	7,307	19.1	32.3	18.0	0.01	81	248
		food cans		0.016	731,000	7,215	17.2	10.3	0.4	1.7	172.0	645	30,100	0.2	3,059	34.1	95.5	25.8	16.34	114	445
		manufactured		0.400	370,000	199	20.0	34.0	0.1	5.6	1,354	194	6,800	0.2	132	7.2	94.0	23.0	5.00	297	400,000
		foil/pack		0.326	337,500	0.8	15.0	27.0	0.2	51.0	134.3	279	8,250	0.8	2,367	40.4	0.004	0.03	0.01	53	120
		other		0.001	850,000	8,389	20.0	12.0		2.0	200.0	750	35,000	0.2	3,557	0.0	111.0	30.0	19.00	132	518
glass	combined	clear		1.52	13,449	1.0	88.8	340.8	1.0	4.8	28.0	22	2,335	0.2	179	10.1	109.3	144.7	0.77	50	60
		green		0.12	10,819	9.8	44.6	486.6	0.4	0.3	943.0	6	2,620	0.1	250	62.7	20.0	36.5	0.06	166	21
		brown		0.13	9,796	6.9	29.2	190.7	0.2	1.7	46.2	92	7,568	0.6	256	22.8	103.1	25.4	0.48	27	251
		other colour		0.02	6,036	0.4	21.5	784.7	0.01	5.4	91.5	29	1,921	0.1	76	12.5	90.0	154.3	0.16	74	1,671
	light bulbs			0.003																	
	fluorescent			0																	
inorganic	light construction	rock/sand/dirt/ concrete/ceramic		0.60	71,574	6.0	2,850	807.8	0.01	20.0	187.0	134	47,949	0.3	1,074	155.8	1,545	200.4	0.79	128	5,118
		drywall/plaster		0.09	490	0.6	288.0	31.0	0.9	2.0	8.6	7	1,090	0.3	21.0	4.2	38.0	38.0	0.20	26	21
		insulation	fglass	0	977	0.7	53.6	296.7	0.1	0.05	14.1	48	919	1.1	102.5	8.2	40.8	5.2	0.03	114	12
			other	0																	
	other			0.87	3,150	17.1	13.2	61.1	0.2	0.4	34.0	112	319	0.1	111.2	23.5	30.1	0.8	0.003	89	57
small appliances	electrical parts	brass & copper		0.08																	
		plastic		0.15	34,368	777.1	11.8	1.4	0.04	3.6	251.3	915	850	0.1	29.6	4.4	662.3	4,802	3,045	80	63
		other metals		0.05																	
household hazardous	batteries	lead acid		0																	
		button		0																	
		carbon		0.011	6,500	2.8	18.0	14.0	0.3	31	39.0	140	12,000	20.5	170,000	278.0	40.0	23	0.04	354	63,000
		ni-cad		0.007	10,000	4.4	70.0	12.0	0.0	120,000	64.0	53	190,000	0.3	2,788	315.0	113.0	670	0.11	53	685
		alkaline		0.012	815	1.0	59.0	7.6	0.3	1,940	74.0	12,000	160,000	242.0	170,000	726.0	143.0	60	0.02	342	140,000
		other		0																	
	other			0.33																	
diapers				2.12																	
household biomedical				0.09																	
bulky waste				0.07																	
fines				7.56	11,000	6.6	45.5	48.0	0.2	4.4	115.0	243	17,500	1.4	532	53.6	258.5	45	0.13	70	654

Paper, plastics and organics make up nearly 70% of the total weight sorted. Individual components within the paper group are highly variable; no single paper category predominated this group. Residual-mixed, corrugate, and black and white newsprint predominate. Individual components within the organics group are also highly variable, but the single largest category is lawn and plant waste (mostly grass and leaves). Only food and wood were found in each of the samples. Colour and flexible plastic film (plastic bags are an example of this category) were present in every sort. All the other plastic components were found in at least one of the sorted samples. No single metals subcategory was found in every sorted sample, but every sorted sample contained some ferrous and non-ferrous metal.

Fines, material passing a $\frac{1}{2}$ in. (12.5 mm) square screen, were found in every sort and made up 7.1% of the MSW as a whole. The amount of fines ranged from 1.0 to 18.1%. The fines found in a sorted sample seems to be related to the makeup of the sample as a whole. For example, if the sorted sample was rich in friable material, such as cheese puffs, then the amount of fines would be high; sorted sam-

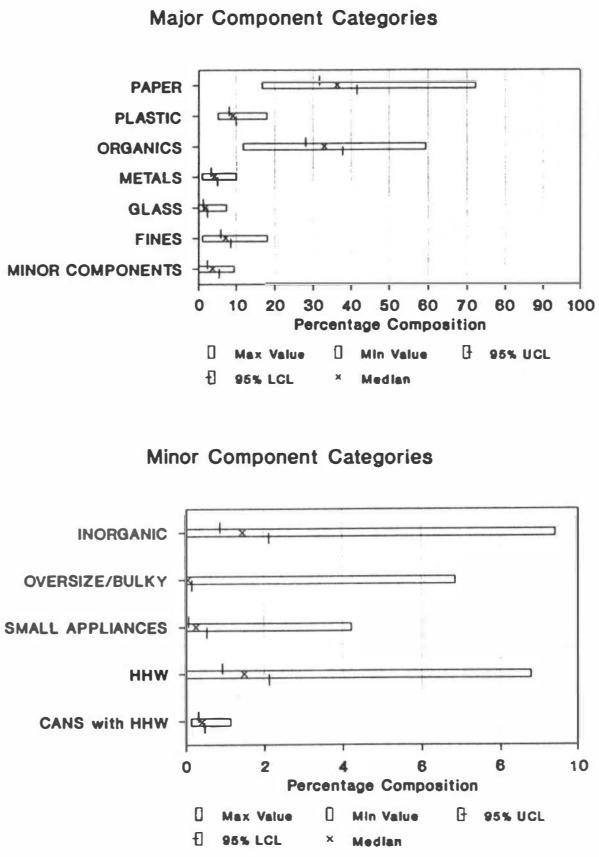

FIG. 2 GRAPHS SUMMARIZING THE SORTING RESULTS FOR WASTE COMPONENT GROUPS

ples with large amounts of clean office paper tended to have lower fines contents.

The amount of plastic, metal and glass components in the waste stream appears to be influenced by the British Columbia deposit laws and the blue-box programs in place in the communities. For example, few plastic containers were found; only limited numbers of metal beverage containers were identified; and, the glass appeared to be predominantly from clear food containers. Inorganic MSW (construction debris) was found in nearly every sort, but made up only a small (1.2%) percentage of the MSW. Only two sorts contained oversize and bulky waste [OBW]. The OBW was pieces of furniture. OBW may have been selectively excluded at the transfer stations supplying solid waste to the GVRD Burnaby incinerator or the pit sampling procedure may have introduced bias by using a wheelbarrow whose size could have excluded OBW. Small appliances, or their broken parts, made up 0.3% of the MSW sorted. Not all the sorts contained material in this category.

Household Hazardous Waste, including potentially biologically contaminated materials, was not present in every sample and comprised 1.5% of the total MSW sorted. The majority of this cate gory was made up of soiled diapers which ranged from none to 5.2% for individual sorts. Batteries were a very small portion making up only 0.03% of the MSW sorted. Most of these were "AA" and "D" carbon and alkaline cells. No button (mercury) batteries were found even though the fines were inspected to see if any of these batteries were present. Neither characteristic tube glass nor end-caps from fluorescent tubes were found during the Burnaby sort. One hypodermic syringe without a needle, some tongue depressors, latex gloves and dental molds were separated.

Hazardous Materials in Containers accounted for 0.4% of the total MSW sorted. This material was mostly aerosol cans, but small (torch-type) propane tanks were found. Interestingly, considering the emphasis placed upon segregating household hazardous waste from the materials subjected to ultimate disposal, the containers did not slosh around indicating that the households were disposing spent containers and not containers filled with substantial quantities of usable materials.

Comparison of the Burnaby data aggregated to form comparable groupings with previous composition studies (Hilton, et al., 1992) indicates that the composition of MSW in the GVRD Burnaby incinerator wasteshed is generally similar to the waste found in other areas with aggressive bottle deposit bills. Containers, particularly beverage bottles, form a substantially smaller proportion of the waste stream than found elsewhere. The principal differences between the sampled Burnaby waste and other bottle bill areas lie in categories that are also addressed by the blue-box system. Newsprint probably represents a reduced proportion of the total waste stream since less was found than other studies would lead us to believe should be present. The blue-box system also seems to be intercepting non-deposit containers. There was insufficient data on the quantity of blue-box diverted materials to draw more precise conclusions.

Metals Distribution Results

A summary of the total metals data grouped at the major category level is provided in Figure 3 and Figure 4 expands the mercury display. The results of lead acid battery and high cadmium PVC pellets and liquid organocadmium compound spiking tests are discussed elsewhere (Chandler, et al., 1992a, Rigo, et al., 1993b).

Paper. Paper accounted for 31.3% of all the mercury found in the waste stream. The majority of the mercury in the paper fraction was found in black and white newsprint and the residual mixed paper fraction. Further tests are needed to determine if these values are the result of contamination picked up in the residual mixed waste paper fraction or a more general consequence of some recycled paper mills preserving wet lath with mercury based fungicides.

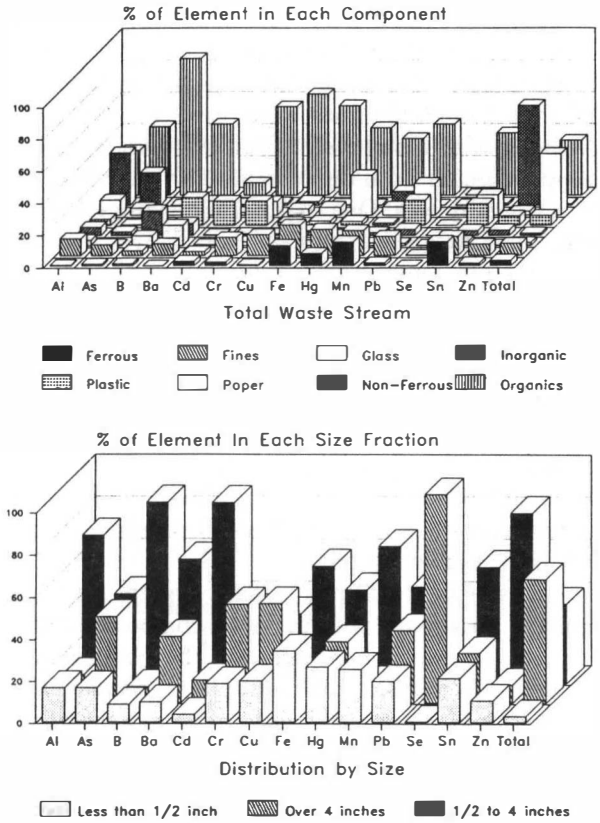

FIG. 3 ELEMENTAL DISTRIBUTION IN THE SAMPLED BURNABY SOLID WASTE STREAM

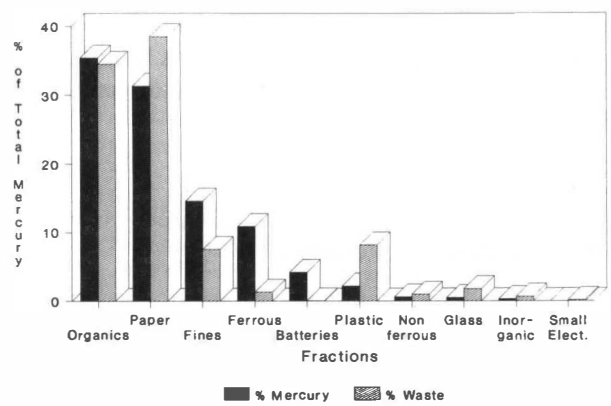

FIG. 4 MERCURY DISTRIBUTION IN WASTE CATEGORIES

Plastics. Plastics contained 2.2% of the mercury in the waste stream. The majority was found in the film plastics.

Organics. Organics contributed the most mercury of any category, 35.4% of the total. More than half was found in the lawn and plant material, 20%, suggesting plant uptake or crustal contributions (entrained dirt) could be significant sources of mercury. Textiles and unfinished wood contributed major portions of organic fraction mercury. The former could be contamination or an intentional preservative used in agricultural textiles; the latter likely the result of uptake by the plants.

Metals. Metal packaging contributed the bulk of the mercury for this category; 10.9% of the total in ferrous and 0.6% in the non-ferrous category. The bulk of the mercury was in a sample of food cans; an off-shore soldered can was included in the lot and mercury could have been a contaminant in the galvanizing. Further work is necessary to confirm this result.

Miscellaneous. Glass, inorganics and small electrical appliances contributed less than 1% of the total mercury in the waste stream. Fines on the other hand contributed the third highest amount of mercury, 14.6%, after lawn and plant material and newsprint. This lends credence to an hypothesis that some of the mercury found in other fractions could be the result of cross-contamination in the mixed waste stream.

Batteries. Batteries contributed only 4.2% of the total mercury load to the waste stream. The 250 PPM levels in the alkaline batteries indicate that Burnaby was already incinerating the new, low mercury batteries when The WASTE Program was conducted. Alkaline batteries contained much higher amounts of mercury than tested carbon batteries.

Analysis of the Mercury Distribution Results

The analytical data in Table 2 can also be used to identify major components that both contribute more than one percent of the element in the total (potentially influence emissions) and have enriched concentrations, (e.g., materials having two or more times the amount of the element as the proportion of the component in the total mix). For instance, batteries made up only 0.03% to the total waste composition, but, after manipulating the data in Table 2, can be found to contain 4.2% of the mercury in the waste stream. Hence, batteries are both a major and an enriched component.

Identifying enriched major contributors is important if source control is an objective because affecting these components will have a disproportionate impact on the mercury content of a tonne of MSW. In addition to batteries, the following components are both major and enriched for mercury:

- black & white newsprint (17.9% mercury in 4.6% of the waste stream);
- grass/plant trimmings (20% in 10.9%);
- ferrous food cans (9.6% in 1.3%); and
- fines (14.6% in 7.6%)

Although not enriched, over 1% of the mercury in the sampled MSW was found in the following major contributor categories:

TABLE 3 ESTIMATED METAL CONCENTRATIONS IN THE WASTE BURNED DURING EACH RUN

ELEMENT	GRAND MEDIAN	RUN RESULTS (PPM) 1	2	3	4	5	6	7	8	9
Number of Sorts	31	2	3	3	2	3	4	5	4	5
Al--aluminum	9654	11344	18176	15548	12050	6012	7942	7082	6883	9242
As--arsenic	7.83	8.12	13.85	10.34	13.27	8.48	3.94	5.60	8.60	9.57
B--boron	110.87	132.14	102.43	145.03	197.24	40.95	130.40	62.46	121.69	125.69
Ba--barium	51.96	56.93	57.83	54.34	78.66	35.31	57.25	43.43	53.29	54.31
Be--beryllium	2.58	1.59	3.04	1.92	2.45	2.45	2.08	2.41	2.74	2.98
Cd--cadmium	13.53	26.37	26.54	4.38	143.14	3.75	19.46	4.14	7.86	5.00
Cr--chromium	92.54	82.77	101.27	89.74	107.07	111.35	75.77	83.52	95.81	113.20
Cu--copper	141.96	136.23	101.41	112.38	704.93	62.22	142.10	73.37	162.83	304.91
Fe--iron	6794	5786	7534	6038	7827	6631	7194	6526	8112	7074
Hg--mercury	0.734	1.445	0.777	0.613	0.977	0.531	0.860	0.613	0.784	0.732
Mn--manganese	271	1137	326	195	534	162	291	193	306	231
Ni--nickel	16.55	21.37	16.22	20.84	21.21	11.55	19.90	14.84	16.89	15.07
Pb--lead	163	152	161	132	145	170	156	191	166	180
Sb--antimony	33	53	29	36	38	33	27	26	46	43
Se--selenium	4.80	1516	0.19	8.02	0.12	7.64	0.75	1.45	9.71	8.41
Sn--tin	49	59	55	45	59	34	52	41	58	47
Zn--zinc	1873	1799	7604	6530	1629	1267	643	1394	258	643

Note: All concentrations in PPM (g/tonne) and at as-disposed moisture content.

- fine/computer/office, corrugated and kraft, and residual mixed paper; and,
- organic wastes including brush, food, finished and unfinished wood and textiles.

Overall, the amount of metals being introduced into the incinerator during each of the 9 runs with sort data are presented in Table 3. The median concentration of mercury during the test program was 0.733 PPM (g/tonne) and exhibited a range of 0.531 to 1.445 PPM (g/tonne) on an as-sampled basis.

WHERE DO THE METALS GO IN AN INCINERATOR?

One aspect of the project was the analysis of waste components as presented above. As noted in the introduction, incinerator residue and exhaust gas streams were also sampled to determine the partitioning of elements. Figure 5 shows the median partitioning of metals observed at Burnaby. In general, metals tend to report to either the bottom ash or fabric filter residue. Mercury is an exception since significant quantities leave with the stack emissions. The boron stack gas concentration may be an artifact of using a borosilicate probe liner. Figure 6 illustrates the disposition of mercury in the various residue and emission streams. Over 99% of the mercury was found in either the APC system residues or the stack emissions.

When all the data are combined, closures for individual element mass balances were determined as the relative percentage difference between inputs and outputs for each balance. Given the inherent variability in the flow measurement, sampling and analytic procedures using propagation of errors techniques estimate that 60% closure typifies this type of experiment (95% confidence level). That is, as long as the difference between input and output for a metal is less than 60% of the average of those two estimates, the run is about as good as can be practically

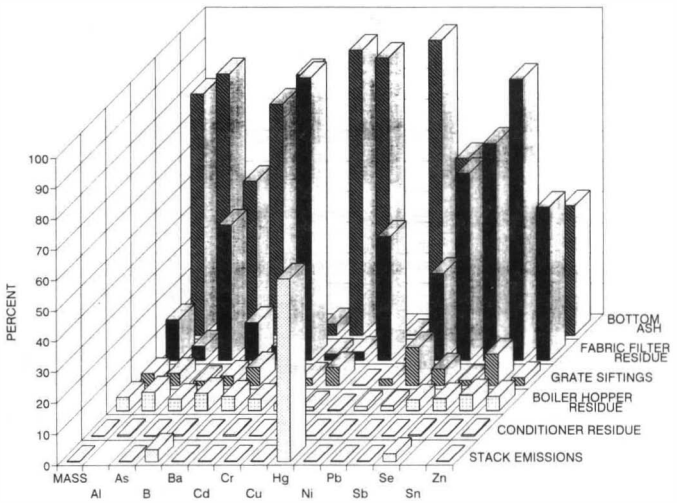

FIG. 5 MEDIAN PARTITIONING OF METALS AT BURNABY DURING THE WASTE PROGRAM

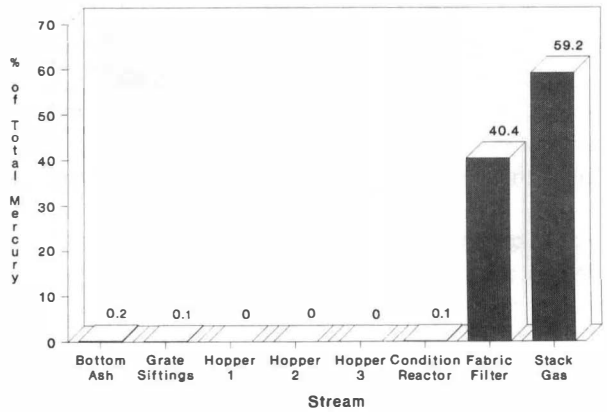

FIG. 6 MEDIAN MERCURY PARTITIONING DURING THE BURNABY TEST

achieved. Most metals generally met the closure criteria. Mercury closure was exceptionally good at about half the target. Barium, copper, nickel and lead all showed high positive deviations indicating that there are unaccounted sources in the MSW feed.

Potential Metal Sources

The complete data set was examined using correlation and Factor Analysis techniques to determine if relationships between components and residue and gaseous emissions could be established. Combining the component distribution and mercury concentration results with the factor analyses results allows causality to be tentatively determined. If the metal is present in meaningful quantities in a component *and* that component is associated with significant concentrations in a residue or gas stream, then there is reason to suspect that the component contributes to mercury emissions. While these analyses cannot establish causality, they do suggest associations to check for credibility and confirm in future assessments. Taking action

TABLE 4 IDENTIFICATION OF WASTE COMPONENTS WITH SIGNIFICANT ELEMENT CONCENTRATIONS OR RELATED TO EMITTED CONCENTRATIONS

Group	Major Category	Minor Category	Sub Category	Al	As	B	Ba	Cd	Cr	Cu	Hg	Ni	Pb	Sb	Se	Sn	Zn
				L P C a b	L P C a b	L P C a b	L P C a b	L P C a b	L P C a b	L P C a b	L P C a b	L P C a b	L P C a b	L P C a b	L P C a b	L P C a b	L P C a b
paper	fine/comp/office																
	books																
	magazines	glued															
		not glued															
	laminates	wax/plastic															
		foil															
	newsprint	glued															
		not glued	b&w														
			colour														
	browns	corrugate															
		kraft															
		box board															
	residual mixed																
plastic	film	colour															
		clear	flexible														
			rigid														
	food/beverage/ household	1 (pete)															
		2 (hdpe)															
		3 (pvc)															
		4 (ldpe)															
		5 (pp)															
		6 (ps)															
		nonidentified															
	housewares	clear															
		white															
		blue															
		yellow															
		other															
	toys and other																
	video tape/film																
organics	yard & garden	lawn/plant															
		branches															
	food waste																
	wood	finished															
		unfinished															
	textiles																
	rubber																
	footwear																
	other																
metals	ferrous	beer															
		soft drink															
		food															
		band & strap															
		manufactured															
	bimetallic	beer															
		soft drink															
		food															
		elect motor															
		other															
	non-ferrous	beer															
		soft drink															
		food															
		manufactured															
		foil/packaging															
		other															
glass	combined	clear															
		green															
		brown															
		other colour															
	light bulbs																
inorganic	light construction	rock/sand/dirt/ concrete/ceramic															
		drywall/plaster															
		insulation	fglass														
			other														
		other															
small appliance	electrical	plastic															
		metal															
household hazardous	batteries	carbon															
		ni-cad															
		alkaline															
fines																	

Note: "LAB" is shaded if component contributes more than 1% of the element to the waste stream and black if it is enriched.
"PC" is shaded if related to only one boiler system response and black if related to grate siftings, bottom ash, stack emissions or more than one boiler system response.

on the basis of potential causality rather than a demonstrated relationship could result in the expenditure of lots of money for no environmental gain.

Table 4 is a semi-graphical summary that identifies components that contribute more than 1% of the metal to the waste stream (LAB column shaded), are enriched (LAB column shaded black) and are related to either residue concentrations or stack emissions (Principal Component-PC-column shaded black). Components that are shaded in both columns may be a significant source of the identified metal in incinerator residues or stack emissions.

For example, mercury stack emissions were positively associated with rigid film plastics, bandages, total household hazardous waste and pesticides in metal cans. There is little mercury in rigid film plastic and conventional wisdom does not indicate a relationship, so it is probably a chance finding. Mercury is an ingredient in some topical medicines and is used as a fungicide in pesticides and other household hazardous waste components; so there may be causality here. A negative association was found with Cleaners-in-Cans indicating that these materials are unusually free of mercury. Batteries are notably absent from this list of components related to stack emissions even though they were sufficiently variable between runs to establish a statistical relationship. Batteries also met the major contributor and enrichment criteria. This suggests that other underlying sources may be more important to mercury emissions than batteries.

Mercury in the grate siftings was related to pesticides in metal cans, brown paper, residual mixed paper, and magazines. Residual mixed paper contained significant quantities of mercury and the pesticides are plausible sources of this metal. The other identified relationships could be happenstance.

Boiler residue mercury was related to rigid film plastics, batteries and cleaners-in-cans. Only batteries are known sources of mercury. The other relationships may be chance alone.

No components are both related to mercury emissions and exhibit sufficient input to result in a tentative identification of causation. Lawn and plant material, newsprint and fines contribute over 50% of the mercury found in the Burnaby waste stream, but these streams lack sufficient quantity variation between runs to establish meaningful statistical relationships. So, they cannot be ruled out as potentially causative.

PERFORMANCE OF MERCURY CONTROL TECHNOLOGY

Mercury emissions control technology is beginning to be applied to waste-to-energy plants. In order to evaluate the likely performance of this technology, a technical framework was derived from USEPA Regulations. Per-

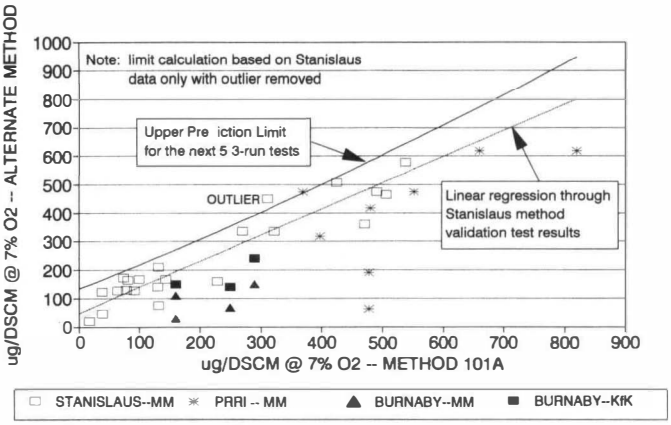

FIG. 7 MULTI-METALS AND OTHER MERCURY RESULTS COMPARED TO SIMULTANEOUS METHOD 101A MERCURY TESTS

mit compliance is usually determined by comparing the arithmetic average of three reference method runs to the limit (40 CFR 60.8(f)). When statistical comparisons are required (see, for example, 40 CFR 60, Appendix B), a 95% statistical confidence level is usually employed. Finally, the Clean Air Act Amendments of 1990 and subsequent implementing regulations limit Title V operating permits for incinerators to 12 years and require them to be reviewed every 5 years.

Since several mercury test methods are currently in use, the first step is to determine if the results are comparable so that observed mercury control system performance at various plants can be compared. OAQPS (1991) performed a methods validation study comparing Method 101A with draft Method 29. During the Burnaby test, sampling trains using Method 101A, Environment Canada's multi-metals method (similar to Method 29) and the KfK (Braun, 1987) dry adsorption tube method (Dowex captures mercury chloride before the balance is caught on iodized activated carbon) were operated in parallel. Parallel Method 101A and Environment Canada multi-metals runs were also conducted at the Peel Resource Recovery Inc. facility in Brampton, Ontario (Air Testing, 1993). At these facilities, simultaneous testing was performed on opposing (perpendicular) traverses so there is an additional source of error.

Figure 7 displays the results of simultaneous mercury measurements at Stanislaus, Burnaby and Peel. The dashed regression line through the simultaneous Stanislaus Methods 29 and 101A data indicates a bias of about 60 μg/DSCM @ 7% O_2 between Methods 101A and 29.

While there is no way of knowing which method is correct, OAQPS (1991) concluded that finding a bias is disturbing and that Method 101A might be missing some of the mercury since Method 29 reported higher values. The Tukey mean-difference plot shown in Figure 8 for the simultaneous Methods 29 and 101A data indicates a single data cluster in the vicinity of 100 μg/DSCM @ 7% O_2 is causing the offset at Stanislaus because the balance

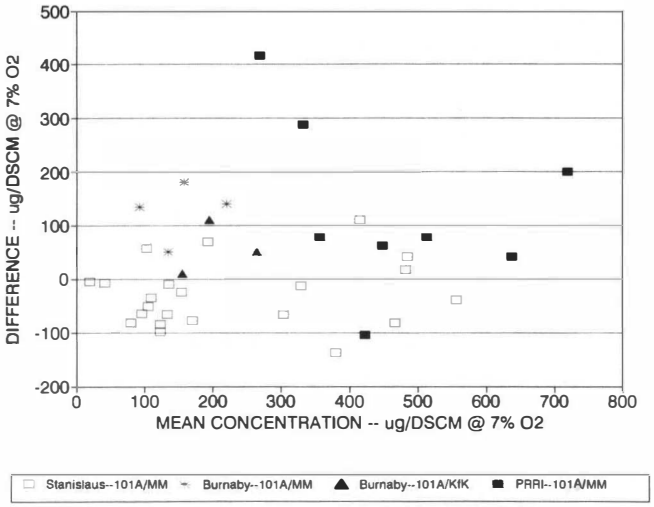

FIG. 8 TUKEY MEAN-DIFFERENCE PLOT COMPARING METHOD 101A MERCURY RESULTS TO ALTERNATIVE METHODS

of the simultaneous run data are scattered about zero. So, the apparent relative bias may be a data artifact and not a methods problem. Additional method development and replicate testing are indicated.

The Burnaby results in Figure 8 shed a little more light. The replicate Methods 101A and 29 Burnaby results parallel the Stanislaus line. An offset is displayed, but the bias is of the opposite sign indicating Method 29 is missing some mercury! On the other hand, the Burnaby KfK and 101A method results do not display any bias (a line drawn through the three duplicate tests parallels the Stanislaus Methods 101A and 29 regression line with a zero intercept). When the simultaneous Methods 101A and 29 data for Peel are considered, most of the data falls along the KfK zero offset line with "outlying" points that are apparently part of the Stanislaus and Burnaby sets.

Fortunately, expanding the data beyond the OAQPS methods validation test indicates that there is probably no difference in the average mercury concentrations measured by Methods 101A and 29. It appears that mercury emissions results — based on Methods 29, 101A or KfK — are comparable and can be combined for analysis.

Finally, a brief examination of uncontrolled mercury emissions finishes setting the stage. Figure 9 is a series of log normal Quantile-Quantile [Q-Q] plots for the uncontrolled mercury emissions measured at the boiler outlet at Stanislaus, CA (OAQPS, 1991); Camden County, NJ (Kilgroe, et al., 1993 and White, et al., 1993a); and Marion County, OR (Richman, et al., 1993). The Marion County data strictly followed Method 101A, so some mercury was probably lost on the unanalyzed laboratory filter residue. These results contain an additional bias.

The Stanislaus and Marion County data are shaped like a hockey stick which indicates the data are described by

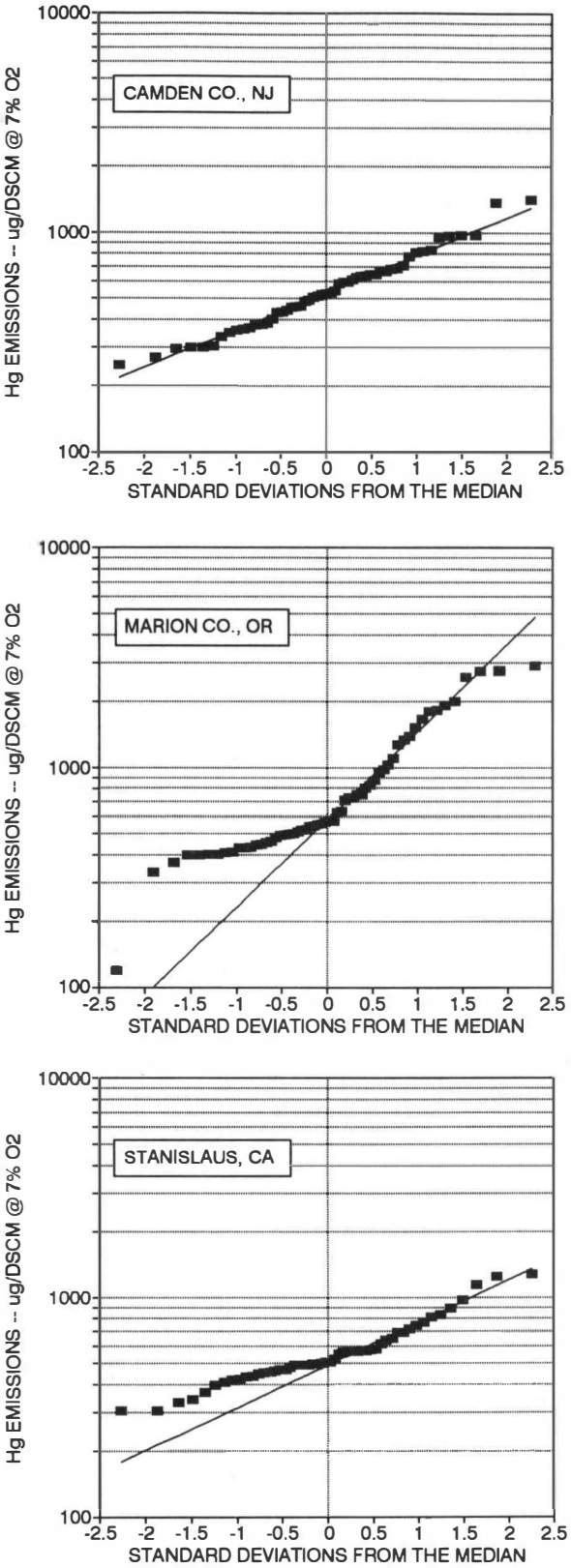

FIG. 9 LOG NORMAL Q-Q PLOTS FOR UNCONTROLLED (BOILER OUTLET) MERCURY EMISSIONS AT CAMDEN COUNTY, MARION COUNTY, AND STANISLAUS

two additive log normal distributions. The lower "blade" of the Stanislaus and Marion County data display essentially the same distribution as all the Camden County data. We speculate that this leveling is indicative of an inherent background mercury level that is not amenable to reduction by increasing the amount of source reduction (i.e. battery and latex paint mercury content reductions) or diversion of readily separable mercury sources (i.e. button battery and fluorescent tube recycling programs). Since biomedical waste was burned during some of the Marion County testing, the upper half of the distribution may be fully explained by the mercury used in many topical ointments and medications.

The data indicates a minimum mercury concentration leaving a municipal waste combustor, before any removal in the air pollution control system, in the range of 200–300 μg/DSCM @ 7% O_2. If so, these concentrations correspond to a potentially irreducible, ubiquitous background mercury concentration between 0.8 and 1.2 PPM (g/tonne) of MSW. Since the MSW mercury content actually measured at Burnaby is comparable, reduction and separation efforts, while undoubtedly beneficial, may miss a majority of the mercury actually present in the waste stream.

Performance of Sodium Sulfide Systems

Because mercury compounds tend to be vapors at spray dryer absorber temperatures, a theoretically attractive control approach is to react the mercury with another chemical to produce a compound that condenses at these temperatures. Forming mercury sulfide appears to fit this bill and was one of the first mercury control methods used on MWCs in North America. The sodium sulfide (Na_2S) is used to convert vapour phase mercury chloride into solid mercury sulfide that can be captured in the fabric filter. At the Burnaby, B.C. facility, the prototype sodium sulfide mercury control system was recently replaced by an activated carbon injection system to eliminate a potential industrial hazard (dissolving sodium sulfide in water liberates small amounts of hydrogen sulfide, an explosive toxic chemical). In-plant testing also indicated that improved mercury removal performance was achieved using activated carbon instead of sodium sulfide at comparable cost (Guest, 1993). This decommissioning indicates that the performance of sodium sulfide based mercury control systems may be of academic rather than practical interest.

During The WASTE Program's Burnaby testing, the incremental mercury removal due to sodium sulfide injection was about 30%. That is, about 30% more mercury was removed using sodium sulfide than is removed by the humidification, dry sorbent injection and fabric filtration system alone. At Stanislaus, the incremental mercury removal was about 35% (Radian, 1991). The Burnaby and Stanislaus results are comparable.

Sodium sulfide injection appears to increase overall mercury removal from about 35% for unaugmented dry scrubber and fabric filter systems operating at 285°F (140°C) to around 55%. This is lower than previously reported performance. Laboratory filters used in the impinger reagent clean-up steps sequester up to 60% of the mercury when sodium sulfide injection is employed (Radian, 1991). So, higher published mercury removal rates for sodium sulfide injection may be testing artifacts.

Performance of Activated Carbon Systems

Activated carbon injection appears to be the control method of choice in North America and much of Europe. Mercury emissions from the Burnaby facility are now controlled this way and several recent MWC permit filings and BACT determinations in the United States include activated carbon injection mercury control technology. Some operating facilities are being retrofitted with activated carbon injection.

In the late 1980s, A/S Niro Atomizer conducted several activated carbon injection demonstration tests in Europe at electrostatic precipitator [ESP] and fabric filter equipped plants. The results of Niro's parametric testing at Zurich Josefstrasse, Amager, and Kassel were summarized by Brown and Felsvang (1991). Since then, the results of the extensive testing conducted at Stanislaus, Camden County and Marion County have been published and three activated carbon mercury control tests reported for the Burnaby installation (Guest, 1993). These data sets provide an excellent basis for proving and calibrating a fundamental engineering model. The model assessment and calibration is, of course, subject to the assumption that the mercury measurement methods employed in the United States, Canada and Europe are all comparable. The preceding discussion of Methods 29, 101A and KfK indicates that such a data compilation is reasonable; however, this assessment of comparability may not satisfy the requirements of Section 129 of the 1990 Clean Air Act Amendments that sampling procedures be validated on solid waste incineration units before they can be specified in federal regulations.

The various authors' original analyses indicate that the type of activated carbon employed (over the range tested), and the method and point of injection are generally unimportant. The Camden County test, however, found that contrary to "no-effect" at Stanislaus, mixing activated carbon into the lime slurry had an effect at this ESP equipped facility. Licata, et al. (1993) observed that activated carbon may not uniformly mix with slurried lime milk and activated carbon pockets have been observed in baghouse filter cakes. If uniform coverage is not achieved, the reduced performance observed at Camden County with slurried coinjection may be the result of a heterogeneous mixture rather than some interfering mechanism. While streaks of activated carbon floating on top of the lime milk were not seen (White, 1993b), mixture homogeneity was not measured. So, the Camden County lime slurry injection runs are treated as suspect and not included in the model cal-

ibration. The Burnaby activated carbon results were kept out of the training set used to calibrate the model. Instead, they were used for model validation.

An engineering model that describes mercury removal efficiency as a function of inlet mercury concentration, particulate control device operating temperature, carbon addition rate and type of particulate control device can be developed from basic principals. Chemical engineers frequently analyze adsorption processes using a Langmuir Isotherm based model. The effect of temperature can be incorporated using van't Hoff's relationship. Changes in the amount of adsorbent are proportional to the activated carbon injection rate or flue gas concentration. After combining, taking logs, rearranging and fitting, the following equation expressed in mixed, but conventional, units describes the data:

$$\mathrm{Ln}(1/E - 1) = 5.63613 - 5618.5/(460 + F)$$

$$- 0.64545 * \mathrm{Ln}(AC + 1) + 0.3934 * \mathrm{Ln}(Hg_{in})$$

$$+ 0.17285 * FF - ESP \qquad (1)$$

where:

E	is the overall efficiency with which mercury is removed
F	is the temperature of the particulate control device in degrees Fahrenheit
AC	is the nominal activated carbon addition rate in mg/DSCM @ 7% O_2
Hg_{in}	is the concentration of mercury measured at the boiler outlet (air pollution control system inlet) in μg/DSCM @ 7% O_2, and
$FF - ESP$	is a dummy variable whose value is 0 if the particulate control device is a fabric filter and 1 if a high efficiency electrostatic precipitator is used.

Robust regression techniques identified 19 of the 199 data points as outliers. Two are the outliers identified in the OAQPS method precision tests (Rigo, 1993c). Most of the outliers are runs with high removal efficiencies and no activated carbon injection. If information were available on the particulate loading leaving the economizer and its carbon content, the offset parameter in the $\ln(AC + 1)$ term could be changed from its current value of 1 to a physically meaningful native carbon loading. This should improve the fit for modern mass burning water wall type combustors and allow extension to other systems which exhibit higher native carbon loadings.

The outliers were assigned a zero weight and weighted least squares regression was used to fit the remaining points, and calculate the coefficients and standard regression statistics. The correlation coefficient is 0.895 and describes more than 80% of the variability in the data. The residuals are normally distributed and the standard-error-of-the-regression is 0.62. The equation was checked by predicting the February 1993 Burnaby efficiency test results. The three results were within a band defined by the standard-error-of-the-regression.

Except for the fabric filter/electrostatic precipitator dummy variable, the coefficients are all statistically significant (at least 0.001 level). Engineering judgement keeps this parameter in the equation because the filter cake has an effect even though the data are too noisy to unambiguously isolate the effect. Also, separate analysis of the electrostatic precipitator and fabric filter data produced essentially equivalent coefficients for the other variables, but the constant was noticeably different.

Equation [1] was used in Monte Carlo simulations to estimate the mercury removal efficiency likely to be observed at fabric filter and electrostatic precipitator equipped facilities using activated carbon injection technology. Monte Carlo techniques combine statistical descriptions of uncontrolled mercury concentrations (log geometric mean 6.1956 and log geometric standard deviation of 4.44935), spray dryer absorber operating temperature (±15°F or ±8.3°C) and specified activated carbon injection rate (geometric standard deviation 0.06), with the statistical characteristics of the activated carbon system performance equation and measurement uncertainty — determined at the 95% confidence level as the root mean square of the measured average and replicate testing error determined to be constant across all concentrations via Tukey mean-difference plots for 3-run averages using the Stanislaus Method 101A validation test results (OAQPS, 1991) — to estimate mercury removal efficiency. Stack mercury concentrations are then calculated for each simulated run by multiplying the uncontrolled boiler outlet mercury concentration and mercury penetration ($1 - E$) estimates. Random values of each parameter are repeatedly selected, and the efficiency and controlled mercury concentrations calculations repeated to develop a large synthetic database (1000 trials) of likely performance. Individual "runs" are then grouped to develop test averages and the highest in each set of five "tests" used to develop limit estimates.

While the results of the Monte Carlo simulation can be no better than the underlying data or assumed model, they do provide considerable insight. Figures 10 and 11 are graphs of the 50th highest 3-run test average and block of five 3-run average test results from 1000 simulations at a series of activated carbon injection rates for a nominal 285°F (140°C) APC operating temperature. 95% statistical confidence level upper tolerance and prediction limits are used to characterize the results.

The *tolerance* limit contains a *specified percentage* of all future test results. The *prediction* limit contains the *next specified number* of tests (Hahn & Meeker, 1991; Rigo, 1993d). These limits are different than the *confidence* limit

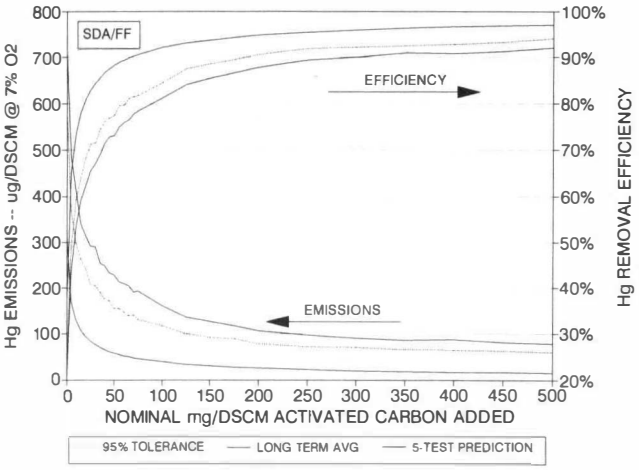

FIG. 10 MONTE CARLO SIMULATION RESULTS SHOWING EXPECTED MERCURY EMISSIONS AND REMOVALS INJECTING INCREASING AMOUNTS OF ACTIVATED CARBON IN AN SDA/FF EQUIPPED MWC

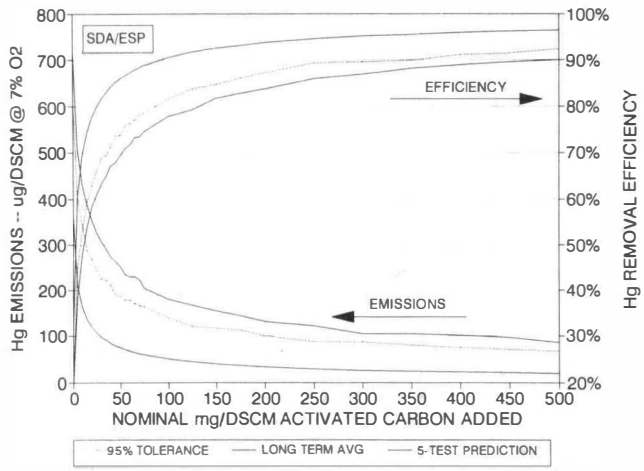

FIG. 11 MONTE CARLO SIMULATION RESULTS SHOWING EXPECTED MERCURY EMISSIONS AND REMOVALS INJECTING INCREASING AMOUNTS OF ACTIVATED CARBON IN AN SDA/ESP EQUIPPED MWC

which most engineers are familiar with. The *confidence* limit bounds the *average*. Since the average is by definition in the middle, half of all normally distributed measurements must exceed this value. The confidence limit estimates long-term performance, but is a woefully inadequate descriptor of what is likely to be actually measured during periodic, routine testing.

Perhaps the biggest difference between confidence and prediction limits is that more testing brings the confidence limit closer and closer to the average, while more testing cannot collapse the prediction (or tolerance, for that matter) interval width to zero. Confidence limits consider only the uncertainty with which the center of the distribution is known. Prediction limits consider *both* the center and how far an individual measurement, or multiple run average, might be located from the center. When more than one future test is involved, joint probabili ties come into play and the band width increases further. In fact, the statistical significance level used in the multiple test calculation becomes the regulatory value divided by the number of complete tests to be bounded. This is 0.01 (99%) for 5 tests to be contained at the 95% statistical confidence level (0.05 significance).

Looking at Figure 10, if 80% control efficiency is to be achieved during testing, the 5 year prediction limit for 3-run averages indicates that the measured mercury concentrations should be less than 180 μg/DSCM @ 7% O_2; annual average removal efficiency will be about 92% and average annual emissions about 50 μg/DSCM @ 7% O_2. If 80% efficiency represents average annual performance, then a consistent test-average stack mercury concentration is 320 μg/DSCM @ 7% O_2, but annual average emissions are about 100 μg/DSCM @ 7% O_2. It should be noted that regardless of the amount of activated carbon used, the 5 test, 3-run average 95% confidence level test limit for mercury does not fall below 80 μg/DSCM @ 7% O_2 even though average annual emissions are asymptotic to about 15 μg/DSCM @ 7% O_2. The electrostatic precipitator system performance described in Figure 11 is similar. The ESP just uses more activated carbon to achieve a specified control level.

Since limits are established at a specified statistical confidence level, there is an inherent probability — 5% or 1 in 20 when using the regulatory 95% confidence level — that a statistically based limit will be exceeded during any individual test when the facility is performing exactly as it did when the data used to set the limit was collected. Either margin must be added to statistically based limits to reduce the possibility of an exceedance due to chance alone, or an immediate retest must be conducted to determine whether an exceedance is a statistical aberration or a real violation. Of course, an operator could make repairs or adjustments to correct an actual problem before retesting. But, isn't encouraging the prompt correction of problems without formal enforcement an important goal of a good program?

CONCLUSIONS

There is a real disparity between the popular perception of the source of some metals in municipal solid waste and their actual location. Mercury is a case in point with household batteries only contributing about 4% to Burnaby MSW. If the objective of waste management is to prevent pollution and dispose of materials in the most environmentally acceptable manner, that is with the fewest adverse effects on the environment and society, then efforts to develop a better understanding of the nature of the

waste stream and the potential effects of different management options need to continue. Failure to do so will waste a lot of time, effort and money.

Since only a few components were statistically related to residue or stack emissions at Burnaby, the presumption that simply separating a metal will proportionately reduce the metal content of a specific stream must be questioned. The overall metal sourcing and partitioning information developed by The WASTE Program shows the societal value of obtaining field data, draws into question the utility of minimization schemes based on popular perception rather than science, and points out the natural presence of significant quantities of metals in materials targeted for composting programs.

Based on the work performed at Burnaby, residue and stack emission data, rather than sort results, can be used to track shifts in input concentrations over time. If sufficient data is collected, the actual effects of intervention can be detected using complete input-output experiments or by identifying significant changes in the distribution of emissions test results after an intervention has taken place.

Finally, there is a significant difference between annual average emissions and testing limits. This difference must be recognized in regulations and permits. Using the relationship between concentration and efficiency found for mercury, as an example, unless the line connecting the prediction limits for the specified values in Figures 10 and 11 is vertical, either concentration or efficiency will be governing. For example, taking limits of 80% removal and 70 μg/DSCM @ 7% O_2, the 5 test, 3-run average prediction limit corresponding to 80% removal is around 170 μg/DSCM @ 7% O_2. So, there is a very good chance that a 70 μg/DSCM @ 7% O_2 limit will be exceeded by one or more tests during a typical operating permit validity period. Since the expected average concentration is less than 50 μg/DSCM @ 7% O_2 for this condition, the source must judge the financial and public perception consequences of a reasonably likely concentration exceedance that is later eradicated by an efficiency retest versus the certain cost of simultaneous inlet and outlet testing. This quandary can be avoided if internally consistent, achievable limits are employed in permits and regulations.

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