CHAPTER 9 - BOTTOM ASH

Bottom ash is the most significant residual by-product from MSW incineration. As noted in Chapters 3 and 8, it accounts for 85 to 95% of all the residues produced during combustion. Bottom ash is usually comprised of grate ash and grate siftings. Occasionally, economiser ashes can be added to the bottom ash process stream. Unless noted otherwise, the data presented in this chapter are for bottom ash. By virtue of combustion temperature and grate design, bottom ash is a slagged material containing lithophilic elements with low vapour pressures. The slagged material is granular. It can be intermingled with ferrous and non-ferrous metal and other uncombustibles if these constituents are present in the MSW prior to combustion.

In Europe, bottom ash is generated as a separate waste stream in the combustion facility. This material is also widely utilised as an aggregate substitute. Consequently, a relatively large data base exists on the physical and chemical properties of bottom ash (Hartlén and Elander, 1986; Ludvigsen and Hjelmar, 1992; Stampfli et al., 1990; van der Sloot, 1992; Vehlow, 1992; Vehlow et al., 1992). Recent interest in bottom ash utilisation in the United States (Chesner et al., 1988; LIRPB, 1993; Eighmy et al., 1992) as well as fundamental ash characterisation studies for a variety of incinerator types in Canada under the NITEP and WASTE programs (Sawell et. al., 1989a; 1989b; 1990a; 1990b; Sawell and Constable, 1988; 1993; Bridl e and Sawell, 1985; PRRI, 1992; WASTE Program, 1993) have also produced large data bases on physical and chemical properties.

Table 9.1 describes the data base that was used to compile data on bottom ash characteristics from around the world. In the table are data from combustors in Canada (seven facilities), Denmark (eight facilities), Germany (three facilities), the Netherlands (five facilities), Sweden (eight facilities) and the United States (eight facilities). The table depicts the type of combustor that is used at each facility, the grates used, the grate manufacturer, the facility capacity (in tonnes per hour) of the combustor units, any bottom ash processing that takes place at the full scale level and various procedures that were used to collect the samples evaluated in this chapter. In all, 39 facilities were evaluated and generated data.

Where possible, time-dependent data on bottom ash characteristics from the Concord, New Hampshire facility in the United States is provided, hereafter referred to as the Concord study (Eighmy et al., 1991). This study, in part, assessed the variability in ash properties collected from 18 sampling events over a 548-day (1.5 year) period. Each sampling event produced four consecutive hourly composite samples and a daily composite. These data allow the reader to assess hourly, daily and seasonal variation in the bottom ash process stream for a typical modern mass burn facility.

Table 9.1 Bottom Ash Database

Country	Facility	Comb. Type[a]	Grate[b]	Manuf[c]	Unit[d] Rating	Bottom Ash[e] Stream Processing	Siftings/ Riddlings[f]	Samp.[i] Period	Reference
Canada	-GVRD	MB	RE	1	10	Q	Yes	1988/92	Sawell et al., 1990a; WASTE Program, 1993
	-GVRD	MB	RE	1	10	Q	No	1992	WASTE Program, 1993
	-PEI	TS	RM	2	1.4	Q	No	1984	NITEP, 1985
	-LVH	TS	RM	2	3.8	Q	No	1088	Sawell et al., 1989a
	-SWARU	FB	Stoker	3	5.4	Q	No	1988	Sawell et al., 1989b
	-QUC	MB	RE	1	10.4	Q	No	1987	Sawell & Constable, 1988
	-3M	TS/RK	-	4	4.1	Q	No	1989	Sawell et al., 1990b
Denmark	-Amagerforbraedingen	MB	MG/RK	5	48	Q,T,<45mm	Yes	1985/91	Lundvigsen &
	-Vesforbraedingen	MB	MG/RK	5	50	Q,T,<45mm	Yes	1985	Hjelmar, 1992
	-KARA, Roskilde	MB	MG	5	20	Q,T,<45mm	Yes	1991	
	-Kolding II	MB	MG	6	8	Q,T,<45mm	Yes	1991	
	-REFA, Nykobing	MB	MG	5	7	Q,T,<45mm	Yes	1991	
	-ASA, Sønderborg	MG	MG	5	10	Q,T,<45mm	Yes	1991	
	-Middlefart	MB	MG	6	4	Q,T,<45mm	Yes	1991	
	-KAVO, Slagelse	MB	MG	6	10	Q,T,<45mm	Yes	1991	
Germany	A	MB	RG	7	10	Q,T,M,<40mm	Yes	1988+	Vehlow, 1992;
	B	MB	RE	1	12	Q,T,M,<40mm	No	1988+	
	C	MB	MG/RK	5	12	Q,T,M,<40mm	Yes	1988+	
Netherlands	-Den Haag	MB	RE	8	25	Q,T,M,<40mm	Yes	1985	TAUW, 1988;
	-AVR	MB	RG	9	21	Q,T,M,<40mm	Yes	1985	Stoelhorst, 1991
	-AVIRA	MB	RE	1	7	Q,T,M,<40mm	Yes	1988	
	-Rotterdam	MB	RE	1	12.5	Q,T,M,<40mm	Yes	1989	
	-Amsterdam	MB	RE	1	45	Q,T,M,<40mm	Yes	1988	
Sweden	-Bollmora	MB	MG	10	2.5	Q	YES	1985	Hartlén & Elander, 1986;
	-Bollnäs	FB	-	11	4.5	Q	YES	1985	SGI, 1993
	-Halmstad	MB	RE	1	10	Q	YES	1985	
	-Linköping	MB	MG	8	31	Q	YES	1985	
	-Malmö	MB	MG	1	25.2	Q	YES	1985	

Country	Facility	Comb. Type[a]	Grate[b]	Manuf[c]	Unit[d] Rating	Bottom Ash[e] Stream Processing	Siftings/ Riddlings[f]	Samp.[i] Period	Reference
	-Högdalen	MB	RG+RE	12	37	-	YES	1985	
	-Umeå	MB	RE	7,13	16.8	-	YES	1985	
	-Uppsala	MB	MG	14,5,6	31	Q	YES	1985	
USA	-SW Brooklyn, NY	-	-	-	-	-	-	-	Chesner, et al., 1988
	-Concord, NH	MB	RE	8	17	Q	Yes	1990/92	Eighmy et al., 1992
	-Glen Cove, NY	-	-	-	-	-	-	-	LIRPB, 1992a,b
	-Dry Scrubber 1	MB	RE	8	4	Q	Yes	1986	LIRPB, 1992a,b
	-Dry Scrubber 2	MB	MG/RK	-	?	?	Yes	1986	LIRPB, 1992a,b
	-Dry Scrubber 3	MB	RE	8	19	Q	Yes	1986	LIRPB, 1992a,b
	-Babylon, NY	-	-	-	-	-	-	-	LIRPB, 1992a,b
	-Massburn	MB	RE	1	20	Q	Yes	1989	Kosson et al., 1992

[a] Combustor Type: MB (mass burn), FB (fluidised-bed), TS (two-stage mass burn).

[b] Grate Type: RK (rotary kiln), MG (moving grate), RG (roller grate), RE (reciprocating grate), V (Vibratory Grate), RM (Ram), TB (travelling bed)

[c] Grate manufacturer. (See numeric legend)

[d] Nominal rating of a unit at the facility in tonnes per hour.

[e] Process stream treated by quenching (Q), trommel (T), grizzly (G), magnet (M).

[f] Are siftings and riddlings blended with the bottom ash that was sampled?

[g] How were samples processed; S (sieving), C (crushing), D (drying).

[h] Where were samples collected; G (end or grate), L (lift), C (conveyor), DC (drag chain), B (bunker), P (pile).

[i] Year of sample collection.

[i] Type of sampling regime; G (grab), C (composites of grabs), T (time-dependent sampling), Z (sampling during altered combustor operation).

1 Martin
2 Consumat
3 Tricil
4 Enercan
5 Vølund
6 Bruun & Sørensen
7 Deutche-Babcock
8 von Roll
9 Dürr
10 Kablitz
11 Generator
12 VKW + Martin/Wehrle
13 KtK ofenbau
14 Widmer + Ernst

9.1 PHYSICAL CHARACTERISTICS OF BOTTOM ASH

9.1.1 Gross Composition

It is important to evaluate the gross composition of bottom ash so that comparisons can be made to soil and other aggregate-like materials. Gross composition is usually comprised of procedures that involve defining a reject fraction, visual classification of the bottom ash, evaluation of the water content of the bottom ash, assessing the concentration of ferrous material in the bottom ash and evaluating the degree of burnout of the combustor and the resulting loss on ignition (LOI) of the bottom ash. All of these parameters are considered gross descriptions of bottom ash and indicate a general environmental and physical quality of the bottom ash.

Reject Fraction

Bottom ash process streams at most modern incineration facilities are processed prior to subsequent utilisation or disposal. This treatment can entail quenching, size separation (trommeling, grizzly separation, magnetic separation) and storage at the incineration facility. Frequently, the trommeling, grizzly separation and magnetic separation of bottom ash produces a reject fraction that comprises some percentage of the total bottom ash process stream generated at the facility. The proportion of the reject fraction depends on materials in the waste feed and the utilisation requirements for the bottom ash. For instance, in Europe, a cutoff size of 40 mm is frequently used. This automatically creates an operationally defined reject fraction that contains large slag and metal pieces. The metal material is usually recovered and recycled. The slag material may be crushed or disposed.

The weight percentage of the reject fractions in Denmark and the United States are shown in Table 9.2. The oversized material reject fraction is typically comprised of ferrous material, nonferrous metallic material, large pieces of slagged bottom ash material, construction debris and unburned MSW. Frequently, this fraction contains enough ferrous to have economic value. The lower limit of the particle size of the reject fraction is determined by the separation system being employed by the facility. In facilities in Denmark, the reject fraction tends to be greater than 45 mm. In the United States, the reject fraction will most likely be greater than either 50 mm or 19 mm, depending on the type of utilisation that is envisioned for the bottom ash. The quantity of reject material that is generated is dependent on the particle size that is being excluded from the bottom ash process stream. In Denmark, at the seven facilities that were evaluated, an average of 6 to 9% (range of 1.3 to 22.7%) of the total bottom ash process stream is rejected by trommels that are removing the greater than 45 mm fraction. This reject fraction contains metals that are both ferrous and nonferrous in nature. It also contains ceramic and glass-like material, as well as slag and unburned material (Ludvgson & Hjelmar, 1992). In the U.S., where the size cut-off tends to be lower for bottom ash utilisation, larger quantities of reject fractions are observed (see Table 9.2). Typically, in the United States, mean reject fractions can be 3.2 to 32.9% (range of 2.4 to 66%) of the total bottom ash process stream. These U.S. data are based on a small percentage of MSW combustion facilities in the U.S. and are not based on mass balances conducted at full scale.

Table 9.2
Bottom Ash Reject Fraction

Country	Facility	Reject Fraction, %					Reference
		Min	Max	Mean	Median	n	
Denmark	Amagerforbraedigen	7.5	12.2	-	-	7	Lundvigsen &
	KARA, Roskilde[a]	1.3	12.6	-	-	7	Hjelmar, 1992
	Kolding II[a]	9.2	22.7	-	-	7	
	REFA, Nykobing[a]	3.5	13.1	-	-	7	
	ASA, Sønderborg[a]	9.4	12.7	-	-	7	
	Middlefart[a]	7.6	11.6	-	-	7	
	KAVO, Slagelse[a]	9.7	16.4	-	-	7	
United States	Southwest Brooklyn, NY[b]	12.1	29.5	19.3	-	170	Chesner et al., 1988
	Concord, NH[c]	21.0	66.0	32.9	31.0	72	Eighmy et al., 1992
	Dry Scrubber 1[b]	6.1	23.8	16.9	-	6	LIRPB, 1992a
	Dry Scrubber 2[b]	2.4	4.0	3.2	-	4	
	Dry Scrubber 3[b]	5.9	12.5	8.4	-	5	
	Dry Scrubber 3[b]	9.8	15.6	12.4	-	5	

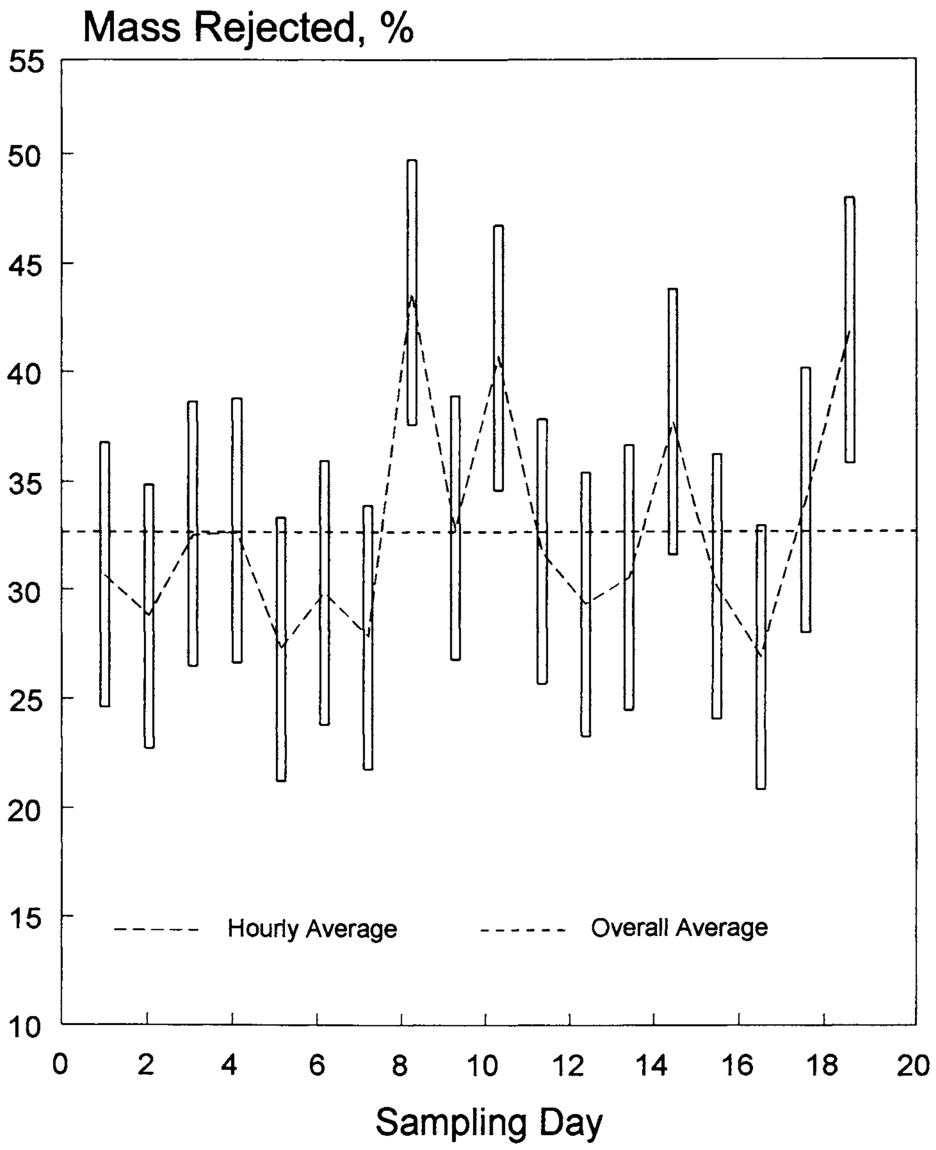
[a] Rejected fraction is the > 45 mm fraction removed from the raw bottom ash; based on wet weight
[b] Rejected fraction is the> 50.8 mm fraction removed from the raw bottom ash; based on wet weight
[c] Rejected fraction is the > 19 mm fraction removed from the raw bottom ash; based on wet weight.

Figure 9.1 shows how the reject fraction percentage can vary over time for the Concord, facility (Eighmy et al., 1992). A reject size of greater than 19 mm was selected to comply with the use of bottom ash in paving applications. This is a smaller particle size cut-off than those typically used in Europe (40 to 50 mm). The data indicates that the reject fraction is relatively constant. The long term variability seen over a 1.5 year period is as variable as the values seen from four consecutive hourly composites within a single sampling day.

Visual Classification

Table 9.3 provides information on the visual classification of bottom ash fractions that are collected for either storage, disposal or utilisation. Data are provided for the Netherlands, Sweden and the United States. The methods for visually classifying bottom ash involves the quantification of the percent composition of metal material, slag material, stone and ceramic material, glass, and organic material. In the data that is available (see Table 9.3), the majority of the fraction that is passed through the size cut-offs is comprised of metal (3 to 46.9%) and slag (27 to 61.8%) material. This

Figure 9.1 Bottom Ash Rejects as a Function of Time



The vertical bars are the 95% Confidence Interval
After Eighmy et al., 1992

combined fraction is typically 50% of the passing material. Often glass is found in concentrations of 10.8 to 44.9% and therefore comprises a major fraction of the material. Ceramics, stones, and organics frequently comprise much lower fractions of this bottom ash process stream.

Table 9.3
Visual Classification Gross Compositional Analysis of Bottom Ash

Country	Facility	% Composition						Reference
		Ferrous %	Slag	Stone	Glass	Ceramic	Organic	
Netherlands	Amsterdam[b]	3	27	34	27	5	4	Stoelhorst, 1991
	Dordrecht[b]	4	29	26	27	7	6	
	Den Haag[b]	7	38	21	21	9	4	
	Rotterdam[b]	6	32	30	20	5	7	
Sweden	Malmö[c]	-	45.0	8.7	44.9	1.3	0.1	Hartlén & Lundgren, 1991
	Malmö[d]	-	55.6	2.0	40.0	2.4	-	
	Malmö[e]	-	50.6	10.1	35.9	3.4	-	
United States	Dry Scrubber 2[f]	16.4 (95)	53.5	-	25.3	4.0	1.0	LIRPB, 1992a
	Dry Scrubber 3[f]	41.5 (98)	37.3	-	16.4	4.4	0.4	
	Dry Scrubber 3[f]	46.9 (97)	33.5	-	17.3	2.4	0.0	
	Babylon, NY[f]	24.3 (86)	61.8	-	10.8	3.3	0.0	

[a] Visual Classification.
[b] Fraction larger than 50 mm.
[c] Fraction between 5.6-8 mm.
[d] Fraction between 8-11.2 mm.
[f] Fraction between 6.35-50.8 mm.

Water Content

The geotechnical water content (or moisture content), as described in Chapter 7, is the weight of water in a sample relative to the oven dry weight of the sample; it is expressed as a percentage. Table 9.4 provides information on the water content of bottom ash materials. Data are presented for both Sweden and the United States. The water content of bottom ash is frequently dependent upon the type of quenching that is utilised to cool the bottom ash. Some incineration facilities utilise a spraying device to quench the ash and this tends to reduce the water content of the bottom ash that is generated. Wet ram systems also produce a drier ash. Other incineration facilities utilise quench tanks with drag chains. This tends to create a bottom ash that has a relatively high water content. The data in Table 9.4 show that typical mean water contents in bottom ash range from 9.4 to 58.4%.

Water content is an important parameter of gross compositional analysis of bottom ash, particularly with regards to its transportation, storage and processing for either disposal or utilisation. It also has an economic impact on transportation and disposal. High levels of water content can increase the weight of material that is being transported and the degree of leachate drag out that is generated at a facility. Water content is usually controlled for utilisation of bottom ash either in granular fill applications, road sub-base applications or asphalt paving applications.

Table 9.4
Bottom Ash Water Content

Country	Facility	Water Content, %					Reference
		Min	Max	Mean	Median	n	
Sweden	Malmö	-	-	16.4	-	13	Hartlén & Rogbeck, 1989
	Malmö	-	-	22.9	-	5	Hartlén & Rogbeck, 1989
United States	S.W. Brooklyn, NY[a,d]	11.3	72.5	27.9	-	62	Chesner et al., 1988
	Concord, NH[b,d]	23.6	65.2	37.8	36.6	65	Eighmy et al., 1992
	Dry Scrubber 1[c,d]	41.0	54.8	46.9	-	4	LIRPB, 1992
	Dry Scrubber 2[c,d]	53.6	63.1	58.4	-	2	LIRPB, 1992
	Dry Scrubber 3[c,d]	15.7	26.4	19.9	-	10	LIRPB, 1992

[a] Fraction less than 50.8 mm.
[b] Fraction less than 19 mm.
[c] Fraction less than 50.8 mm.
[d] ASTM D2216
[e] Aged Ash.
[f] Fresh Ash.

Frequently, the drying of bottom ash and the aging of bottom ash outdoors allows for evaporative losses of water contents that can reduce the water content levels. Work by Hartlén and Rogbeck (1989) has shown that the water content can drop from 23 to 16% upon aging. Frequently the heat of hydration that is generated while the ash ages is high enough to cause significant evaporative losses to take place. Dewatering can also cause water loss. Some water can be taken up into crystalline structures during aging reactions. These tend to be less important loss or transformation reactions than evaporation. Maintaining some level of moisture allows for the bottom ash to remain in aggregated form and prevents fugitive dust problems. Recent work by Chesner (1993) has indicated that moisture contents above 15% are helpful in preventing fugitivity in outdoor storage piles.

Ferrous Content

Table 9.5 provides information on the ferrous content of the bottom ash fractions that are considered for disposal or utilisation. Data are shown for the Netherlands and the United States. In spite of trommelling, the bottom ash passing the reject cut-off can contain appreciable ferrous material as determined by magnetic separation techniques. The evaluation of the ferrous content of bottom ash is important with regards to economics and its potential utilisation, and also with regards to evaluation of a recyclable component of the bottom ash. The ferrous content of bottom ash fractions that are considered for utilisation or disposal tends to range from 0.4 to 43.5% for all samples. Typical mean values are 1.3 to 25.8%. The variation is due to MSW feed composition and to methods in determining the ferrous content.

Figure 9.2 provides information on the grain size distribution of ferrous particles in bottom ash (Eighmy et al., 1992). As can be seen, the ferrous content tends to predominate in the coarser fractions, suggesting that larger particles are predominately ferrous materials. The relative predominance of ferrous material in bottom ash is dependent upon the MSW feed composition and the size cut-offs that are used for producing bottom ash process streams. Figure 9.3 provides information on how the ferrous content varies as a function of time at the Concord facility (Eighmy et al., 1992). As can be seen in the figure, the ferrous content seems to be relatively constant over a 548-day period. The long-term variability seen over a 1.5 year period is as great as the variability seen over four consecutive hourly composites within a single sampling day.

Table 9.5
Bottom Ash Ferrous Content

Country	Facility	Ferrous Content, %					Reference
		Min	Max	Mean	Median	n	
Netherlands	AVI 1[a,b]	0.4	4.4	1.3	-	29	TAUW, 1988
	AVI 2	0.6	8.7	3.18	-	26	
	AVI 3	0.9	3.6	2.32	-	26	
	AVI 4	0.6	3.3	1.59	-	20	
United States	Concord, NH[c,d]	13.4	43.5	25.8	25.1	72	Eighmy et al., 1992

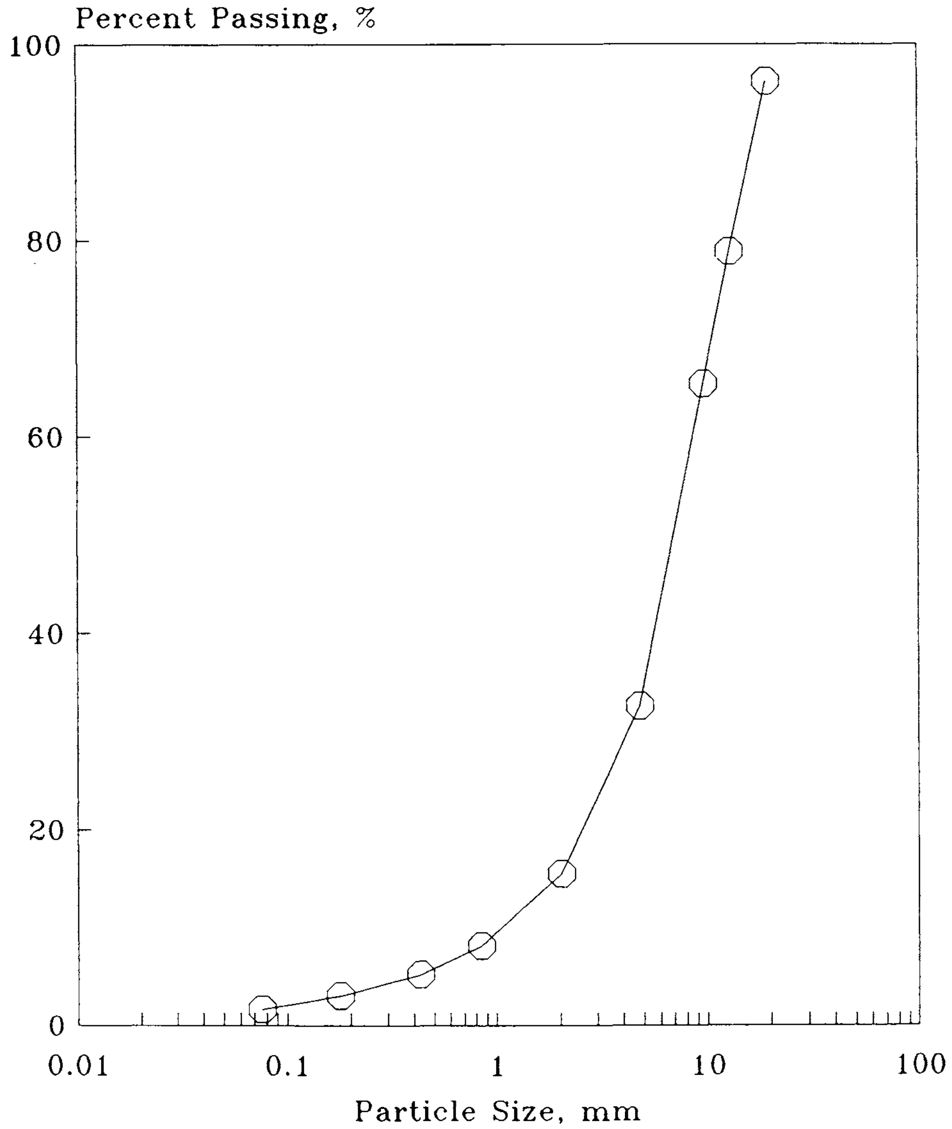
[a] Fraction less than 45 mm.
[b] Method based on magnetic separation.
[c] Fraction less than 19 mm.
[d] Method based on magnetic separation.

Loss on Ignition

Loss on ignition (LOI) is the weight fraction (expressed as a percentage) of material that is lost during ashing at 550°C for two hours. Table 9.6a provides information on the LOI values for bottom ashes from Canada, Denmark and the United States. LOI is an important parameter to measure in bottom ash because it is a gross measure of the relative burnout of the combustor that is generating the bottom ash. Data from Switzerland (Stämpfli, 1992) suggests that up to 60% of the LOI is organic carbon; the remainder is carbonates and tightly bound water of hydration. LOI values can be a function of the type of MSW feed, combustor type and its operation, the relative moisture content of the MSW that is being combusted and the type of combustor operations that are taking place. As can be seen for data presented in Table 9.6a, typical mean values for bottom ashes in Canada range from 3.5 to 29.2%. Denmark mean values range from 1.9 to 6.3%. In the United States mean values range from 3.7 to 6.4%. Values of approximately 3% or less indicate a high degree of burnout (Brunner et al., 1987).

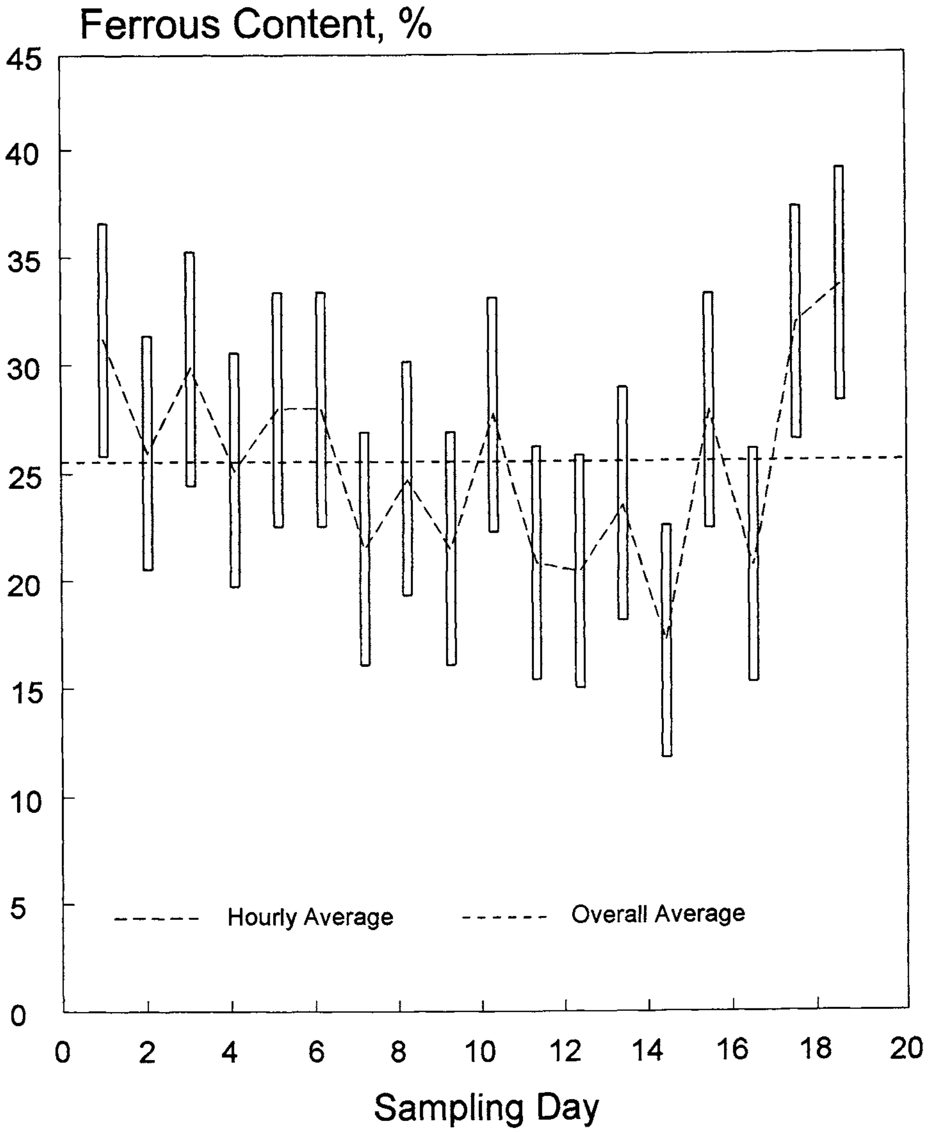
Based on data gleaned from the NITEP, the WASTE Program and other Canadian studies, significant differences in LOI are found as function of combustor type. As shown in Table 9.6b, the LOI content of bottom ash collected from poorly operated two-stage combustion systems was much higher (20 to 30% LOI values) than ash from

Figure 9.2 Particle Size Distribution of Ferrous Materials from Bottom Ash



After Eighmy et al., 1992

Figure 9.3 Bottom Ash Ferrous Content as a Function of Time



The vertical bars are the 95 % confidence intervals
After Eighmy et al., 1992

Table 9.6a
Bottom Ash Loss on Ignition

Country	Facility	Loss on Ignition, %					Reference
		Min	Max	Mean	Median	n	
Canada	GVRD	2.5	2.6	2.65	-	4	Sawell et al., 1990a
	PEI	23.6	33.4	28.4	-	8	Bridle & Sawell, 1986
	LVH	-	-	29.2	-	2	Sawell et al., 1989b
	SWARU	-	-	4.9	-	2	Sawell et al., 1989a
	QUC	-	-	3.5	-	12	Sawell & Constable, 1988
	3M	18.7	22.1	20.4	-	4	Sawell & Constable, 1990b
Denmark	Amagerforbraending[a,f]	6.1	6.5	6.3	-	3	Luvigsen & Hjelmar, 1992
	KARA, Roskilde[a,f]	2.6	2.8	2.7	-	3	
	ASA, Sønderborg[a,f]	2.4	2.8	2.5	-	3	
	REFA, Nykøbing[a,f]	3.1	3.8	3.4	-	3	
	Kolding II[a,f]	2.2	2.3	2.2	-	3	
	KAVO, Slagelse[a,f]	1.7	2.2	1.9	-	3	
	Middlefart[a,f]	3.8	4.5	4.1	-	3	
United States	Southwest Brooklyn,NY[b,g]	1.4	10.5	4.3	-	62	Chesner et al., 1988
	Concord, NH[c,g]	3.2	10.7	6.4	6.2	72	Eighmy et al., 1992
	Dry Scrubber 1[d,h]	3.5	4.0	3.7	-	4	LIRPB, 1992a
	Mass burn[e,g]	4.4	4.9	4.6	-	3	Kosson et al., 1992
	Mid-Conn	0.6	1.5	-	-	-	Sawell et al., 1991

[a] Fraction less than 45 mm.
[b] Fraction less than 50.8 mm.
[c] Fraction less than 4.75 mm.
[d] Fraction less than 50.8 mm.
[e] Fraction less than 2.0 mm, with crushing of over size material.
[f] Loss on ignition at 550°C.
[g] ASTM C 114.
[h] ASTM D 2974.

Table 9.6b
Bottom Ash Loss on Ignition

Combustor Type	LOI Content (%)	Reference
Two-stage (poor operation)	18.7 - 29.2	Sawell & Constable, 1993
Two-stage (good operation)	12.6 - 16.5	Sawell & Constable, 1993
Older mass burn	2.5 - 3.5	Sawell & Constable, 1993
Modern mass burn	0.1 - 1.7	WASTE Program, 1993
Older RDF	4.9	Sawell & Constable,1993
Modern RDF	0.6 - 1.5	Sawell & Constable, 1993

either mass burn or semi-suspension combustion systems (LOI values less than 5%). Two-stage systems employ semi-pyrolytic operating conditions in the primary chamber to produce energy-rich flue gases which are then passed into a highly-oxidative secondary combustion chamber. As a result, the bottom ash contains a relatively high proportion of uncombusted material. It should be noted that although some of these data were collected from poorly operated systems, even well operated two-stage systems generate bottom ash with LOI contents in the range of about 10% without special primary chamber modifications. The results also indicate that modern mass burn and RDF systems are capable of achieving low LOIs (<2%).

Figure 9.4 shows the loss on ignition of bottom ash as a function of bottom ash particle size (Eighmy et al., 1992). As can be seen, there are two maxima, one at a larger particle size (10 mm) which is uncombusted char material and paper. The other tends to be at very small particle sizes (< 0.25 mm) and reflects the fact that very fine materials in bottom ashes can be organic materials.

Figure 9.5 shows how bottom ash LOI changes as a function of time at the Concord, New Hampshire facility (Eighmy et al., 1992). The data indicate that the LOI content from 18 sampling events over the 1.5 year period is relatively constant and is as variable as the variability seen within four consecutive hourly samples within a single sampling day.

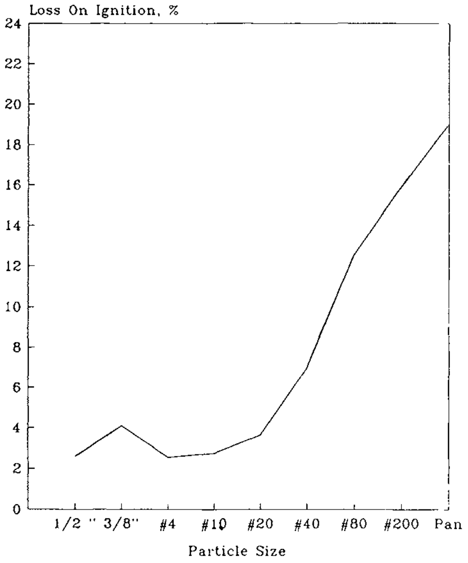
Dissolvable Solids Content

Some limited data are available on the dissolvable solids content of bottom ash. The content is directly related to the soluble mineral content of the residue. The data come from the NITEP and WASTE program studies (Sawell and Constable, 1993; WASTE Program, 1993). The sequential batch extraction procedure was used to evaluate the leaching properties of various bottom ashes from a variety of North American facilities. One aspect of the extraction test is that total dissolved solids can be determined in the leachates. They can be summed for the four sequential extractions and related to the initial weight of ash. The data show that two-stage bottom ashes have the lowest dissolvable solids content (2.5 to 4.5%). Modern mass burn bottom ashes range from 3.0 to 14%. One RDF facility had bottom ashes with values ranging from 6.5 to 7.5%. The data indicate that more complete mineralisation (e.g. better burn-out) increases the soluble mineral content of the bottom ash.

9.1.2 Gravimetric Characteristics

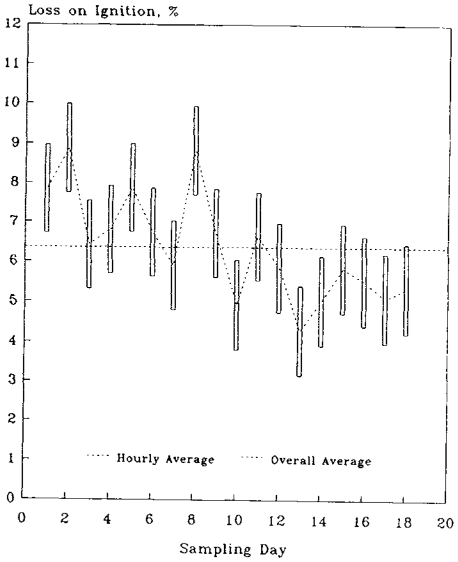
Gravimetric characteristics of bottom ash are important in evaluating the civil and geotechnical properties of bottom ash. These calculations are needed in designing Portland cement and asphalt job mixes as well as in evaluating field densities of these materials.

Figure 9.4 Bottom Ash LOI as a Function of Particle Size



After Eighmy et al., 1992

Figure 9.5 Bottom Ash LOI as a Function of Time



The verticle bars are the 95% intervals
After Eighmy et al., 1992

Specific Gravity

Specific gravity is defined as the ratio of the weight of a given volume of a sample to the weight of an equal volume of water at standard temperature and pressure. It is reported as a dimensionless number. Specific gravity is usually a very important parameter to measure in bottom ash when consideration is given to utilising bottom ash in civil engineering construction. The procedure for determining specific gravity is usually conducted on two specific size fractions of granular materials. Usually the fine fraction is material less than 4.75 mm in diameter. The coarse fraction is material larger than 4.75 mm in diameter.

Table 9.7a provides data on bulk specific gravity of bottom ash materials from facilities in the United States. The data from the Concord facility show that the fine fraction has a mean value of 1.86, with ranges of 1.49 to 1.86. The coarse fraction has a mean value of 2.19, with ranges of 1.82 and 2.43.

There seems to be good uniformity among the determinations of the bulk specific gravity from the facilities that were evaluated within the United States. These values classify bottom ash as a lightweight aggregate.

Table 9.7b provides information on the saturated surface dry (SSD) specific gravity of bottom ash from a number of facilities in the United States. The data from the Concord facility show that the fine fraction has a mean value of 2.13, ranging from 1.81 to 2.37. The coarse fraction has a mean value of 2.35, with a range for individual values of 1.90 to 2.41. There are good agreements between the bulk specific gravity determinations (SSD) between the facilities within the United States.

Table 9.7c provides information on the bottom ash apparent specific gravity from a number of facilities in the United States. The data from the Concord facility show that the fine fraction has a mean value of 2.55 with a range of 2.11 to 2.93. The coarse fraction has a mean value of 2.51 with a range of 2.28 to 2.93. Again, there is good agreement between the different facilities.

Figure 9.6 shows the variation of bulk specific gravity as a function of time at the Concord, New Hampshire facility (Eighmy et al., 1992). As can be seen in the figure, the coarse bulk specific gravity does exhibit some variability as a function of time over the 1.5 year sampling period. The fine bulk specific gravity is less variable; the variation seen within any four consecutive hourly composite samples in a day is similar to the variation seen over the long term. Evaluation of apparent specific gravity and bulk specific gravity saturated surface dry shows similar behaviours as a function of time.

Absorption

Absorption is used to calculate the change in weight of an aggregate due to the absorption of water into permeable pore spaces within aggregate particles. Bottom ash

Table 9.7a

Bottom Ash Specific Gravity

Country	Facility	Bulk Specific Gravity									
		Fine[d]					Coarse[e]				
		Min	Max	Mean	Median	n	Min	Max	Mean	Median	n
United States	Concord, NH[a,c]	1.49	2.13	1.86	1.88	72	1.82	2.43	2.19	2.19	72
	Dry Scrubber 2[b,c]	-	-	-	1.81	1	-	-	-	2.11	1
	Dry Scrubber 3[b,c]	-	-	-	1.70	1	-	-	-	2.17	1
	Dry Scrubber 3[b,c]	-	-	-	1.76	1	-	-	-	2.23	1

Table 9.7b

Country	Facility	Bulk Specific Gravity (SSD)									
		Fine[d]					Coarse[e]				
		Min	Max	Mean	Median	n	Min	Max	Mean	Median	n
United States	Concord, NH[a,c]	1.81	2.37	2.13	2.12	72	1.90	2.41	2.35	2.33	72
	Dry Scrubber 2[b,c]	-	-	-	2.03	1	-	-	-	2.21	1
	Dry Scrubber 3[b,c]	-	-	-	1.98	1	-	-	-	2.26	1
	Dry Scrubber 3[b,c]	-	-	-	2.04	1	-	-	-	2.30	1

Table 9.7c

Country	Facility	Apparent Specific Gravity										Reference
		Fine[d]					Coarse[e]					
		Min	Max	Mean	Median	n	Min	Max	Mean	Median	n	
United States	Concord, NH[a,c]	2.11	2.93	2.55	2.56	72	2.28	2.83	2.51	2.50	72	Eighmy et al, 1992
	Dry Scrubber 2[b,c]	-	-	-	2.31	1	-	-	-	2.35	1	LIRPB, 1992a
	Dry Scrubber 3[b,c]	-	-	-	2.38	1	-	-	-	2.38	1	
	Dry Scrubber 3[b,c]	-	-	-	2.45	1	-	-	-	2.41	1	

[a] Fraction less than 19 mm.

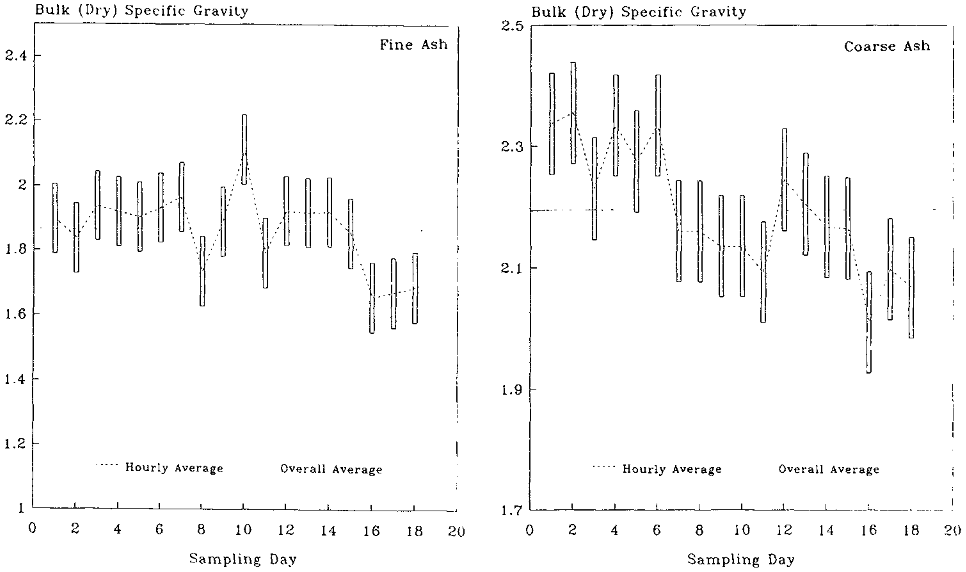
[b] Fraction less than 50.8 mm.

[c] ASTM C127, C128.

[d] Fraction less than 4.75 mm.

[e] Fraction greater than 4.75 mm.

Figure 9.6 Bottom Ash Bulk Specific Gravity as a Function of Time



The vertical bars are the 95 % confidence interval
After Eighmy et al., 1992

is a highly porous aggregate, therefore it has the tendency to absorb water. The absorption of water is also a useful predictor for the potential for bottom ash to absorb asphalt during the manufacturing of asphaltic cement or to retain water during field compaction. Table 9.8 provides data on absorption characteristics for bottom ashes from United States facilities. As with specific gravity, absorption is evaluated for both fine and coarse fractions. For the fine fraction, a mean value of 14% is seen with minimum values of 7.6% and maximum values of 27.9% for all measurements. For coarse fraction, a mean value of 5.7% is seen, with minimum and maximum values ranging from 1.7 to 13.4% for all measurements. There is good agreement between values from the different facilities in the United States. The fact that absorption values are higher for the fine fraction again supports the contention that the fine fraction is a highly porous material with a high surface area to volume ratio that has the capacity to absorb large quantities of water. Most natural aggregates have lower absorption values.

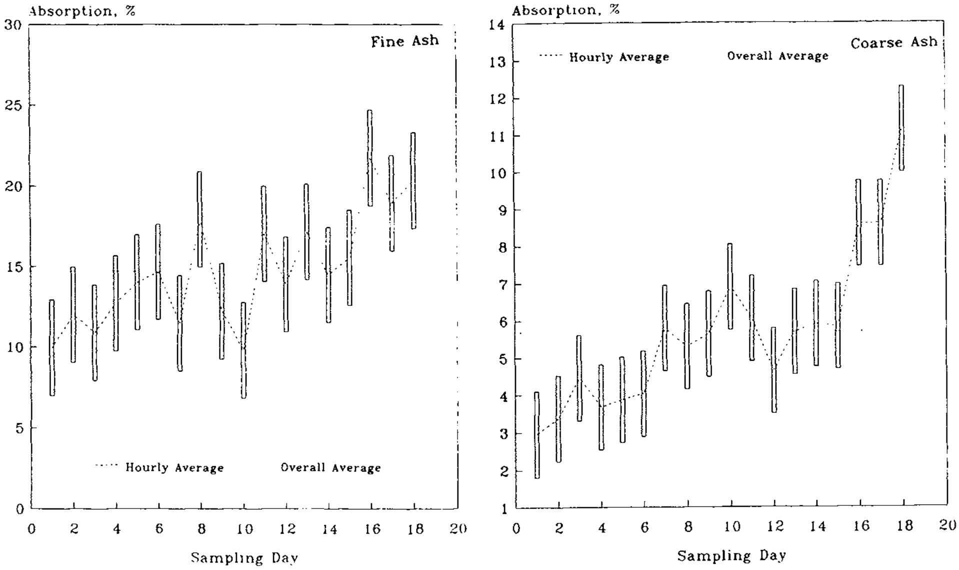
Figure 9.7 shows the variation in bottom ash absorption as a function of time for the Concord, New Hampshire facility (Eighmy, et al., 1992). The long-term variability seen over a 1.5 year period is slightly greater than the variability seen within four consecutive hourly composites within any single sampling day.

Table 9.8
Bottom Ash Absorption

Country	Facility	Absorption, %										Reference
		Fine[b]					Coarse[c]					
		Min	Max	Mean	Median	n	Min	Max	Mean	Median	n	
United States	Concord, NH[a]	7.6	27.9	14.7	14.0	72	1.7	13.4	5.7	5.4	72	Eighmy et al., 1992
	Dry Scrubber 2[a]	-	-	-	12.0	1	-	-	-	4.7	1	LIRPB, 1992a
	Dry Scrubber 3[a]	-	-	-	17.0	1	-	-	-	4.1	1	
	Dry Scrubber 3[a]	-	-	-	16.1	1	-	-	-	3.2	1	

[a] ASTM C127, C128. [b] Fraction < 4.75 mm. [c] Fraction > 4.75 mm.

Figure 9.7 Bottom Ash Absorption as a Function of Time



The vertical bars are the 95 % confidence intervals

After Eighmy et al., 1992

Unit Weight

Table 9.9 provides information on bottom ash unit weight from a number of facilities in the United States and Canada. Typical mean values range from 955 to 1,420 kg/m^3. Typical minimum and maximum values are 732 and 1,510 kg/m^3 for all measurements, respectively. There is reasonably good agreement about bottom ash unit weight values for each of the facilities that were evaluated. These unit weight values show that bottom ash is a lightweight aggregate.

Table 9.9
Bottom Ash Unit Weight

Country	Facility	Unit Weight, kg/m^3					Reference
		Min	Max	Mean	Median	n	
Canada	GVRD	1,370	1,510	1,420	-	4	WASTE Program, 1993
United States	Southwest Brooklyn, NY[a,b]	732	1,229	1,054	-	62	Chesner et al., 1988
	Concord, NH[a,c]	1,039	1,234	1,157	1,159	20	Eighmy et al., 1992
	Dry Scrubber 1[a,b]	1,090	1,183	1,152	-	4	LIRPB, 1992a
	Dry Scrubber 2[a,b]	955	956	955	-	2	
	Dry Scrubber 3[a,b]	1,102	1,378	1,215	-	5	
	Dry Scrubber 3[a,b]	1,150	1,312	1,234	-	5	

[a] ASTM C29. [b] Fraction less than 50.8 mm. [c] Fraction less than 19 mm.

Figure 9.8 shows bottom ash unit weight as a function of time at the Concord, New Hampshire facility (Eighmy et al., 1992). As can be shown in the figure, bottom ash unit weight was relatively constant over the 1.5 year sampling period.

9.1.3 Gradation

Figure 9.9 shows a typical bottom ash grain size distribution. The distribution is classified as well-graded, meaning that there is equal abundance of coarse and fine material. Such uniform gradation is important to the compactability of bottom ash and the potential to utilise bottom ash as an aggregate substitute.

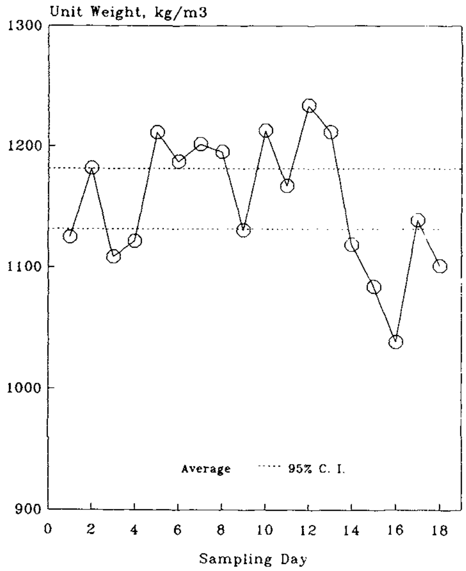
Table 9.10 provides information on bottom ash effective size and uniformity coefficients. Effective size is determined by calculating the grain diameter where 10% of the material is passing. Coefficient of uniformity is the ratio of the grain diameter in millimetres corresponding to 60% passing by weight to the effective size of that material. As can be seen in Table 9.10 the mean effective size of bottom ash is 0.293 mm. Minimum and maximum values for all measurements are 0.127 and 0.508 mm. The mean uniformity coefficient was 21.6 with minimum and maximum values of 12.8 and 38.0. The data that are shown in Table 9.10 are from only one facility in the United States. The effective size and uniformity coefficients indicate that bottom ash is a well-graded gravelly sand.

Table 9.10
Bottom Ash Effective Size and Uniformity Coefficients

Country	Facility	Effective Size, mm					Uniformity Coefficient					Reference
		Min	Max	Mean	Median	n	Min	Max	Mean	Median	n	
USA	Concord, NH[a]	0.127	0.508	0.293	0.254	72	12.82	38.0	21.68	20.68	72	Eighmy et al., 1992

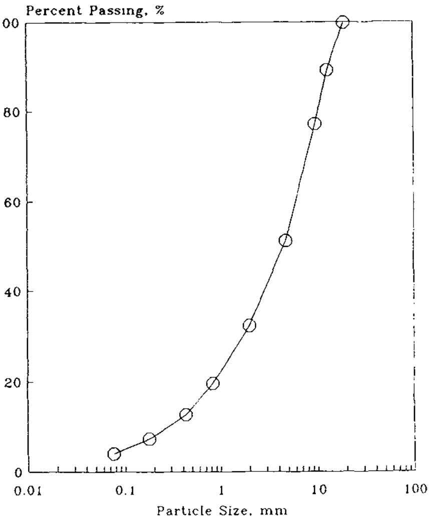
[a] Fraction less than 19 mm.

Figure 9.8 Bottom Ash Unit Weight as a Function of Time



After Eighmy et al, 1992

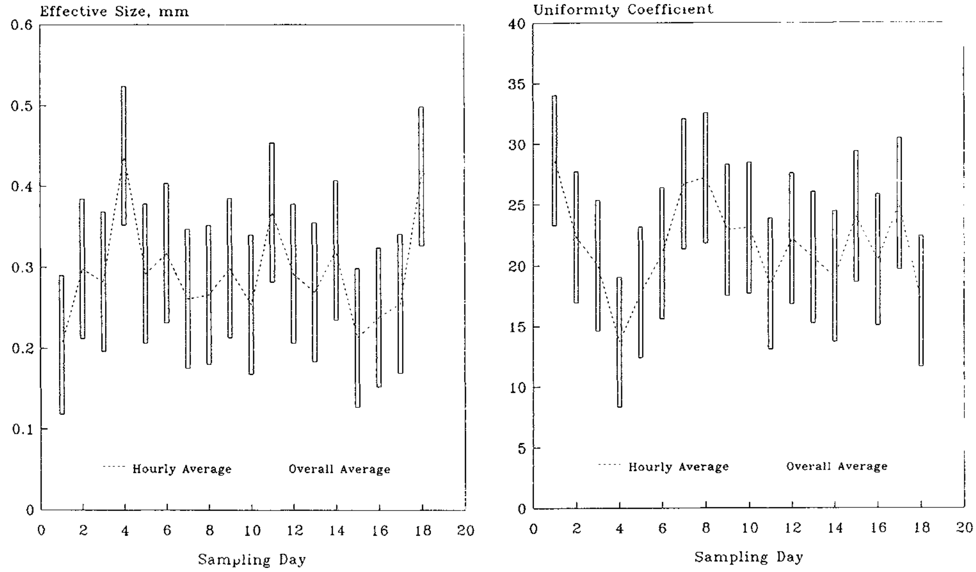
Figure 9.9 Bottom Ash Grain Size Distribution



After Eighmy et al., 1992

Figure 9.10 shows how bottom ash effective size and uniformity coefficients vary as a function of time for bottom ash samples obtained from the Concord facility. The data indicate that both effective size and uniformity coefficient were reasonably constant over the 1.5 year sampling period.

Figure 9.10 Bottom Ash Effective Size and Uniformity Coefficient as a Function of Time



After Eighmy et al., 1992

Percent Fines

The concentration of fine material in bottom ash is an important consideration when bottom ash is to be used as an aggregate substitute. The percent fines can frequently create problems because that fraction is highly absorptive for water, asphaltic cement and Portland cement. Frequently, high fine contents create a material that has a tendency towards freeze-thaw susceptibility and durability failure. The values for percent fines shown in Table 9.11 are from facilities in Germany, the Netherlands and the United States. The fraction denoting fines can be different in Europe compared to the United States. In Europe a fine fraction is usually denoted as that material passing a 63 μm mesh sieve. In the United States, a fine fraction is denoted as that material passing a 75 μm mesh sieve. Nevertheless, mean values for fines range from about 1.9 to 7.4%. Minimum and maximum values for all measurements are 1.0 and 10.1% respectively. There is good agreement between the values seen from the different facilities in the different countries.

Table 9.11
Bottom Ash Percent Fines

Country	Facility	Fines, %					Reference
		Min	Max	Mean	Median	n	
Germany	A[a]	2	7	4	-	5	Vehlow, 1992
	B1[a,b]	3	8	5	-	4	
	B2[a,c]	2	7	5	-	4	
	C[a]	2	6	4	-	4	
Netherlands	AVI 1[a]	6.2	9.5	7.3	-	29	TAUW, 1988
	AVI 2[a]	3.7	7.2	5.9	-	26	
	AVI 3[a]	4.8	9.6	7.4	-	26	
	AVI 4[a]	4.3	10.1	7.3	-	26	
United States	Southwest Brooklyn, NY[d,e]	1.0	3.2	1.9	-	62	Chesner et al., 1988
	Concord,NH[d,e]	2.17	6.57	3.96	3.92	72	Eighmy et al., 1992
	Dry Scrubber 3[d,e]	2	3	2	-	10	LIRPB, 1992a
	Dry Scrubber 3[d,e]	1	3	2	-	10	

[a] Fines denoted as fraction passing 63 µm.
[b] Unit 1
[c] Unit 2
[d] Fines denoted as fraction passing 75 µm.
[e] ASTM C136 (dry sieving technique).

As bottom ash exhibits some friability, the production of fines during processing operations may occur. The levels of fines in bottom ash are somewhat problematic with regards to the utilisation of bottom ash in civil engineering construction applications because fines increase water capillarity and promote frost susceptibility. This means that under certain utilisation scenarios this fine fraction may need to be removed from the bottom ash process stream. At certain ash processing facilities in Europe, fines are removed by trommeling processes using agricultural trommels.

Figure 9.11 shows how percent fines vary as a function of time at the Concord facility (Eighmy et al., 1992). The data indicate that the fine fraction was relatively uniform over the 1.5 year sampling period. The variations seen over time were as great as the variations observed within four consecutive hourly sampling events.

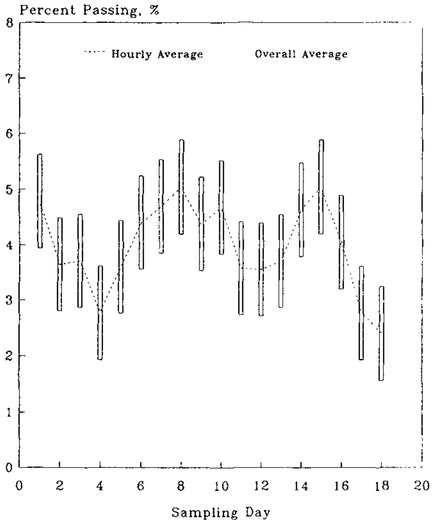
9.1.4 Durability

The assessment of the durability of bottom ash is an important characterisation when considering the utilisation of bottom ash. Frequently, bottom ash is considered as an aggregate substitute and it is important to characterise how durable bottom ash is in comparison to natural aggregates.

Soundness

The sodium or magnesium sulphate soundness test is generally the accepted method for aggregate soundness testing. Data are provided in Table 9.12 on percent losses observed to bottom ash samples subjected to soundness testing. The data are from facilities in the United States. Soundness testing usually involves evaluation of both fine (< 4.75 mm) and coarse (> 4.75 mm) fractions. The data shown in Table 9.12 indicate that for the fine fraction, mean percent losses ranged from 1.6 to 11.91. The coarse fraction mean values were 2.6 and 2.9. As with sorption, the fine fraction is more susceptible to expansive fragmentation compared to the coarse fraction. This is because bottom ash fine material is more porous than the coarse material. There is a wide variation in values for the fine fraction seen between facilities within the United States. It is not clear as to why this variation exists.

Figure 9.11 Bottom Ash Percent Fines as a Function of Time



The vertical bars are the 95% confidence intervals
After Eighmy et al., 1992

Abrasion Resistance

The Los Angeles abrasion test measures the ability of an aggregate material to maintain its physical integrity under defined abrasive conditions. The test is conducted on two different size fractions, a coarse and a fine fraction, termed "B" and "C", respectively. The test is considered to be highly aggressive with respect to evaluating lightweight porous aggregate materials. Table 9.12 provides data on LA abrasion resistances for bottom ash B and C fractions from facilities from the United States. Typical percent losses observed for both fractions are around 40 to 45%. These values are considered to be high, however they are typical for porous lightweight aggregate materials.

Table 9.12
Bottom Ash Durability

Country	Facility	Soundness, % Loss[a]									
		Fine					Coarse				
		Min	Max	Mean	Median	n	Min	Max	Mean	Median	n
United	Concord, NH[c]	10.38	14.32	11.91	11.48	4	2.51	2.76	2.63	2.63	4
States	Dry Scrubber 1[d]	1.7	3.4	2.7	-	4	-	-	-	-	4
	Dry Scrubber 3[d]	1.1	2.4	1.6	-	5	1.6	4.0	2.9	-	5

Country	Facility	LA Abrasion, % Loss[b]											
		B Fraction					C Fraction						
		n	Min	Max	Mean	Median	n	Min	Max	Mean	Median	n	Reference
United	Concord, NH[c]	4	46.4	48.2	47.3	47.3	2	42.6	44.2	43.4	43.4	2	Eighmy et al., 1992
States	Dry Scrubber 1[d]	-	57.8	58.5	58.2	-	4	40.4	40.7	40.6	-	2	LIRPB, 1992a
	Dry Scrubber 2[d]	-	-	-	-	-	-	43.1	46.1	44.6	-	2	
	Dry Scrubber 3[d]	5	57.6	61.0	59.6	-	5	44.9	48.3	46.6	-	5	
	Dry Scrubber 3[d]	-	46.0	61.8	54.9	-	6	41.3	47.5	45.0	-	6	

[a] ASTM C88.
[b] ASTM C131.
[c] Original fraction less than 19 mm.
[d] Original fraction less than 50.8 mm.

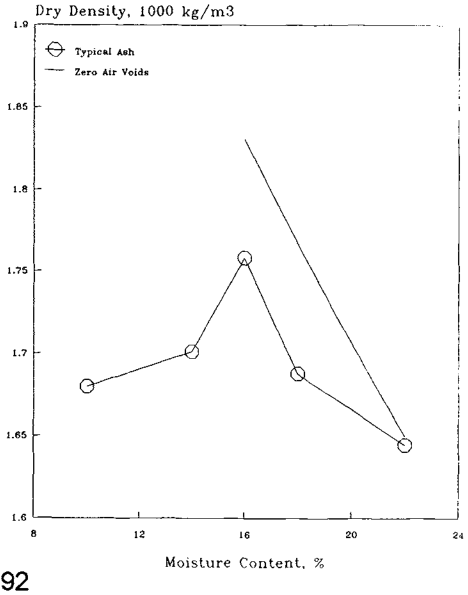
9.1.5 Geotechnical Properties

Many of the utilisation scenarios envisioned for bottom ash involve the use of bottom ash as an aggregate substitute subjected to compaction. Despite the potential problems of durability with bottom ash, bottom ash is a highly compactible material that upon compaction has high levels of E-modulus and strength. The fine fraction in bottom ash, the retentive capacity of bottom ash for holding water and the porosity of bottom ash mean that careful attention must be given to bottom ash water content prior to compaction.

Proctor Compaction

The compactibility of a granular material is frequently assessed in the laboratory using Proctor compaction testing. Figure 9.12 shows a typical Proctor compaction curve with an optimum moisture content at maximum dry density. Table 9.13 provides data on bottom ash Proctor moisture optimums as well as maximum Proctor densities. Data are provided from facilities from the Netherlands, Sweden and the United States. As can be seen in the table, mean Proctor densities range from 1530 to 1739 kg/m^3. The minimum and maximum values that are observed are 1242 to 1838 kg/m^3 for all measurements. Good agreement is seen between facilities from the different countries. The geotechnical moisture content, at which maximum compaction occurs, tends to range from about 9.6% to 20%, with typical mean values of 13 to 16%. These moisture optimums are similar to those seen for gravelly sands in their ability to allow compaction to occur. There is good agreement between facilities from different countries with regard to moisture optimums that are observed.

Figure 9.12 Bottom Ash Proctor Compaction Curve



After Eighmy et al., 1992

Table 9.13
Bottom Ash Proctor Moisture and Proctor Density Compaction

Country	Facility	Proctor Density (kg/m^3)					Proctor Moisture (% WC)					Reference
		Min	Max	Mean	Median	n	Min	Max	Mean	Median	n	
Netherlands	AVI 1^a	1,513	1,665	1,602	-	29	11.9	16.5	13.3	-	29	TAUW, 1988
	AVI 2^a	1,543	1,630	1,573	-	26	10.9	16.0	13.0	-	16	
	AVI 3^a	1,445	1,620	1,530	-	26	10.6	18.7	14.2	-	26	
	AVI 4^a	1,475	1,630	1,530		20	9.6	16.5	12.9		20	
Sweden	Malmö^b	-	-	-	1,825	1	-	-	15.5	-	1	Hartlén & Rogbeck, 1989
United States	Concord, NH^c	1,619	1,838	1,739	1,748	18	12.0	16.0	15.4	16.0	18	Eighmy et al., 1992
	Dry Scrubber 1^d	-	-	-	1,345	1	-	-	-	12.8	1	LIRPB, 1992a
	Dry Scrubber 2^d	1,242	1,298	1,271	-	2	15.0	17.0	16.0	-	2	
	Dry Scrubber 3^d	1,500	1,588	1,545	-	5	14.3	14.8	14.6	-	5	
	Dry Scrubber 3^d	1,550	1,580	1,566	-	5	20.8	21.7	21.3	-	5	
	Mass burn^d	-	-	-	2,463	1	-	-	-	16.6	1	Kosson et al., 1992

[a] Standard Proctor.

[b] Standard Proctor.

[c] ASTM D1557 (Modified Proctor).

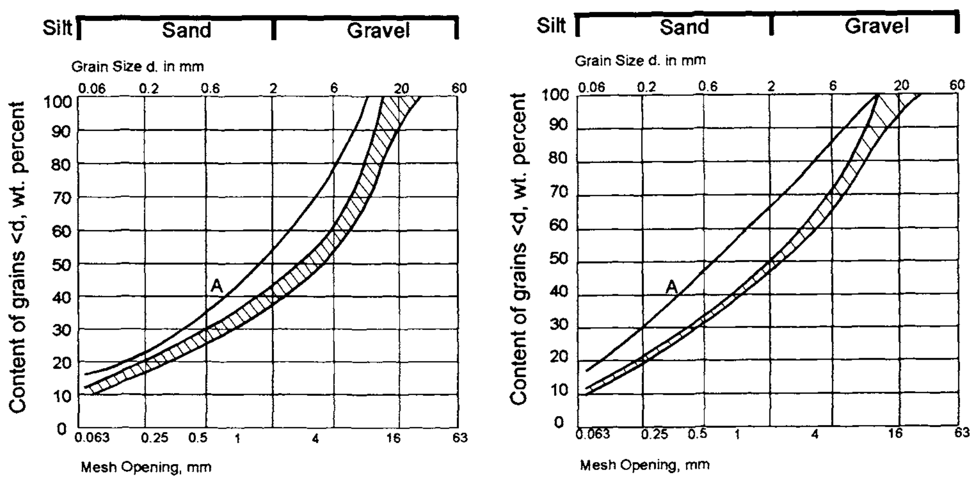
[d] ASTM D1557 (Modified Proctor).

The E-modulus can be evaluated for bottom ash materials as a function of Proctor compaction. Work by Hartlén and Elander (1986) shows very high E-modulus values for ashes compacted in the fresh form and aged. The E-modulus values that are observed indicate that bottom ash is a strong aggregate material when it is in a compacted state.

Field Compaction

Field compaction can be an aggressive, energetic process. Frequently, the compaction methods that are used in the field can break down particles in bottom ashes. Figure 9.13 shows how bottom ash particle size distributions become finer after field compaction efforts. The data, provided by Hartlén and Rogbeck (1989), show that most full scale field compactors will fracture and fragment bottom ash and change the grain size distribution. At this time it is not clear if the degree of grain size redistribution is problematic with respect to civil engineering structural fill applications. Many bottom ash utilisation studies have shown that bottom ash can be successfully used as a compacted aggregate material in road sub-bases or in wind barriers and embankments. However, the fines content may require control as this influences frost susceptibility in cold climate applications.

Figure 9.13 Bottom Ash Particle Size Distribution after Field Compaction



2 months old

1 year old

The shaded area represents the original grain size distribution
The solid line (A) shows the new grain size
After Hartlén and Rogbeck, 1991

California Bearing Ratio (CBR)

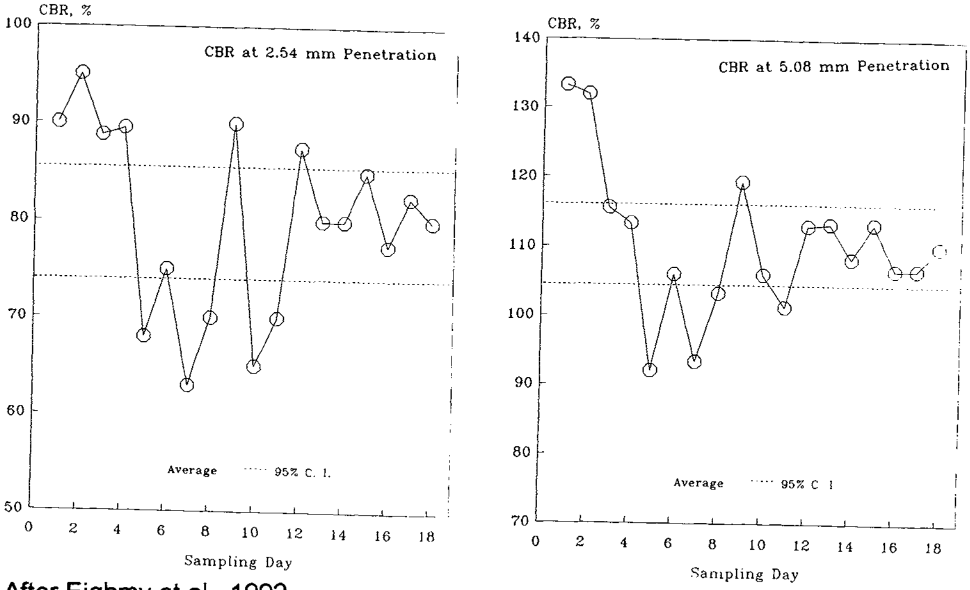
The CBR is a determination of the strength and stability of a compacted material. Values greater than 100% for CBR are seen in bottom ash. Table 9.14 provides information on CBR values at 0.1 inches and 0.2 inches for bottom ash samples obtained from facilities in either the Netherlands or the United States. Mean values seen at 0.1 inches range from 51.8 to 79.7% with minimum values at 22 and maximum values of 112.5 for all measurements. The CBR at 0.2 inches is higher. Typical mean values are 39.0 to 154.5%, with minimum and maximum values ranging from 32.0 to 167.3% for all measurements. There is not good agreement between the data from different countries, but it is not clear why.

Table 9.14
Bottom Ash Penetration Resistance

Country	Facility	CBR @ 0.1 Inches[a]					CBR @ 0.2 Inches[a]					Reference
		Min	Max	Mean	Median	n	Min	Max	Mean	Median	n	
Netherlands	AVI 1	24.0	65.0	52.0	-	29	32.0	76.0	62.4	-	29	TAUW, 1988
	AVI 2	38.0	62.0	51.8	-	26	52.0	74.0	61.2	-	26	
	AVI 3	22.0	42.0	31.7	-	26	28.0	50.0	39.0	-	26	
	AVI 4	27.0	46.0	34.1		20	34.0	58.0	42.1		20	
United States	Concord, NH	63.0	112.5	79.7	80.0	20	92.0	136.5	110.2	107.5	20	Eighmy et al ,1992
	Dry Scrubber 1	-	-	-	-	1	-	-	-	146.0	1	LIRPB, 1992a
	Dry Scrubber 2	-	-	-	-	2	121.0	158.7	139.9	-	2	
	Dry Scrubber 3	-	-	-	-	5	122.7	167.3	154.5	-	5	
	Dry Scrubber 3	-	-	-	-	5	38.7	126.0	90.1	-	5	

Figure 9.14 shows how CBR varies as a function of time at the Concord facility. The data show that CBR exhibits some variability as a function of time.

Figure 9.14 Bottom Ash CBR as a Function of Time



After Eighmy et al., 1992

9.1.6 Permeability

The permeability of bottom ash, or its ability to transmit water via percolation, is an important component with regards to characterising the hydraulic regime to which bottom ash can be subjected. Because bottom ash is a well-graded material and can be compacted to high densities, it is expected that under compactive efforts the permeability of bottom ash will be quite low. Frequently, an assessment of the permeability of bottom ash is needed to model leaching of bottom ash, to model water balances of water moving through bottom ash and to assess the ability of bottom ash to freely drain.

Utilising permeability testing apparatus, permeabilities that have been observed in bottom ash are usually in the low 10^{-6} cm per second range. Table 9.15 shows some bottom ash permeabilities obtained in studies conducted in both Denmark and Sweden. At maximum density, it appears that bottom ash permeability can range from about 0.2 to 10.0 x 10^{-6} cm/s. Such permeabilities are considered to be relatively low for well-graded materials and reflect the presence of fine material which increases the tortuosity within bottom ash. Such low permeability values suggest that bottom ash may be subject to some infiltration but could also create some surface runoff.

Table 9.15
Bottom Ash Permeability

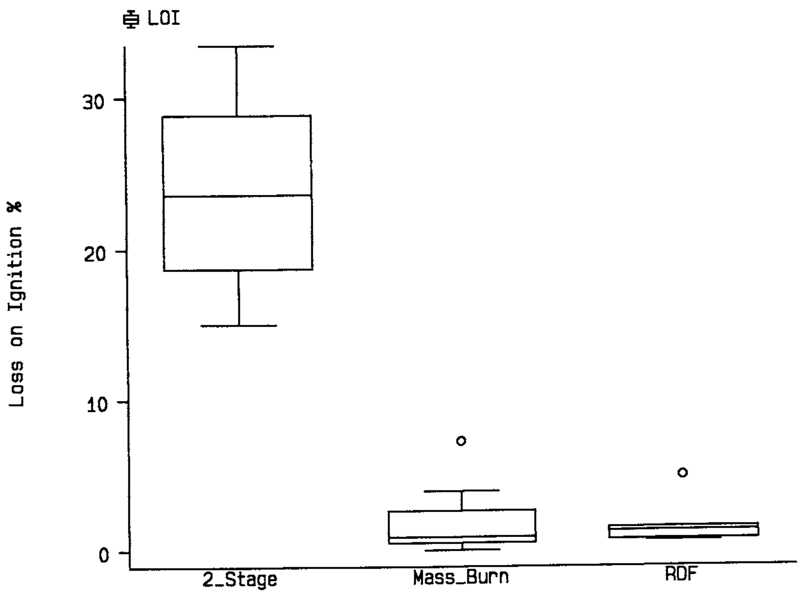
Country	Facility	Permeability 10^{-6} cm/s	Reference
Denmark	-	3.5-4.4	Geoteknisk Institute, 1992
Sweden	Malmö	0.2-10.0	Hartlén & Elander, 1986

9.1.7 Influence of Combustor Type and Operation on Physical Characteristics

There has not been a great deal of study conducted on the influence of combustor type and combustor operation on the physical properties of bottom ash. The comprehensive NITEP program was the only large scale study that has been conducted to date that has looked at the influence of poor combustor operation and combustor type on ash characteristics. The only data that is available at this time is information on the loss on ignition content for a variety of facilities operated under both good and bad conditions.

As shown in Figure 9.15, two-stage systems operated either under good or bad conditions produce bottom ash with significantly higher LOI values than mass burn or RDF systems.

Figure 9.15 Influence of Combustor Type on Bottom Ash LOI



9.1.8 Influence of Aging on Bottom Ash Physical Characteristics

There have been some studies conducted in Sweden, Germany and the U.S. on the influence of aging on certain physical characteristics of bottom ash.

In Sweden, it has been shown by Hartlén and Rogbeck (1989) that the E-modulus of bottom ash will increase as bottom ash ages over time when compacted at optimum moisture under Proctor compaction testing. This increase in strength is attributable to the formation of mineralogical phases that increase particle interlocking within the bottom ash. Additional studies on aging in Sweden from bottom ashes at the Malmo facility have shown that when ash is aged for almost a year, the Proctor compaction characteristics are much better than when ash is freshly collected (Hartlén and Elander, 1986). Again, aging is thought to increase the formation of certain mineralogical phases that increase the durability of the residue and interlocking characteristics of the particles in the residue.

Studies in Sweden have also evaluated the influence of aging on the gross composition gradation of bottom ashes generated from the Malmo facility. There do not appear to be any significant differences between the nonmagnetic fraction, the glass fraction, the ceramic material, stone material and organic material in either fresh or aged fractions (Hartlén and Lundgren, 1992).

Studies have been conducted in Germany to look at the influence of aging on a number of civil engineering properties. The data, presented by Vehlow (1992), show the influence of aging on leachable solids in bottom ash as bottom ash ages. The concentration of leachable solids in bottom ash decreases during aging. This is particularly true for facilities A and C (see Table 9.1). Facility B did not exhibit the same trends. The susceptibility to freeze/thaw fracturing has also been evaluated for aged materials in German facilities and the data suggests that the susceptibility to freeze/thaw erosion decreases with aging. This is particularly true again for facilities A and C. The data from facility B does not support this observation.

Also evaluated in the German study was the raw density of aged material compared to fresh material at the three facilities. In all cases the raw density tended to increase with aging. This phenomenon is not presently understood.

9.2 PARTICLE MORPHOLOGY, MINERALOGY, AND ALKALINITY OF BOTTOM ASH

Particle morphology, mineralogy and alkalinity of bottom ash play important roles in both the physical and chemical characteristics of bottom ash. The particle morphology of bottom ash is an important component in its physical characteristics and performance because of the angular nature of bottom ash particles. Bottom ash also tends to be a rough-textured material and this is an important property with regards to its physical performance. The mineralogy of bottom ash is thought to be important to understanding the leaching behaviour of bottom ash; however, the mineralogy also plays an important role in the compactibility and strength development of bottom ash as it ages with time. Finally, buffer capacity is an important component for both physical and chemical performance because of the role of the carbonate buffer system in bottom ash and the influence that has on strength development, particle aging and leaching.

9.2.1 Morphology

Figure 9.16 provides some scanning electron microscopy micrographs and petrographic thin section micrographs of bottom ash particles. As can be seen in the SEM micrographs, bottom ash is an angular material. Slag-like material can be seen; the slag material is porous and contains vesicles. The petrographic thin section of bottom ash clearly shows that bottom ash possesses a high degree of internal porosity that is connected to the exterior of the particles. This vesicle porosity provides a large surface area for chemical reactions to take place and for leaching phenomenon to occur. As shown in Table 9.16, a number of researchers have looked at the specific surface area of bottom ash using BET absorption isotherms. Typically, bottom ashes have surface areas of 3 to 46 m^2/g dry weight of bottom ash. These are considered to be very high degrees of surface area for a granular material. For instance, traditional soils have surface areas that are orders of magnitude less than that. Mercury porosimetry is also used to look at internal pore diameters as can be seen in Table 9.16. A number of the pores in the material are considered to be quite small in nature. Values of less than a tenth of a micron are seen. The data also suggest that combustor type has an influence on the type of surface area and pore diameter that is found in bottom ash. The reader should refer to Chapters 12 and 13 for further discussion on the role of surface area in chemical leaching phenomenae.

Figure 9.16 SEM Micrographs (a,b) and Petrographic Thin Section Micrographs (c,d) of MSW Bottom Ash

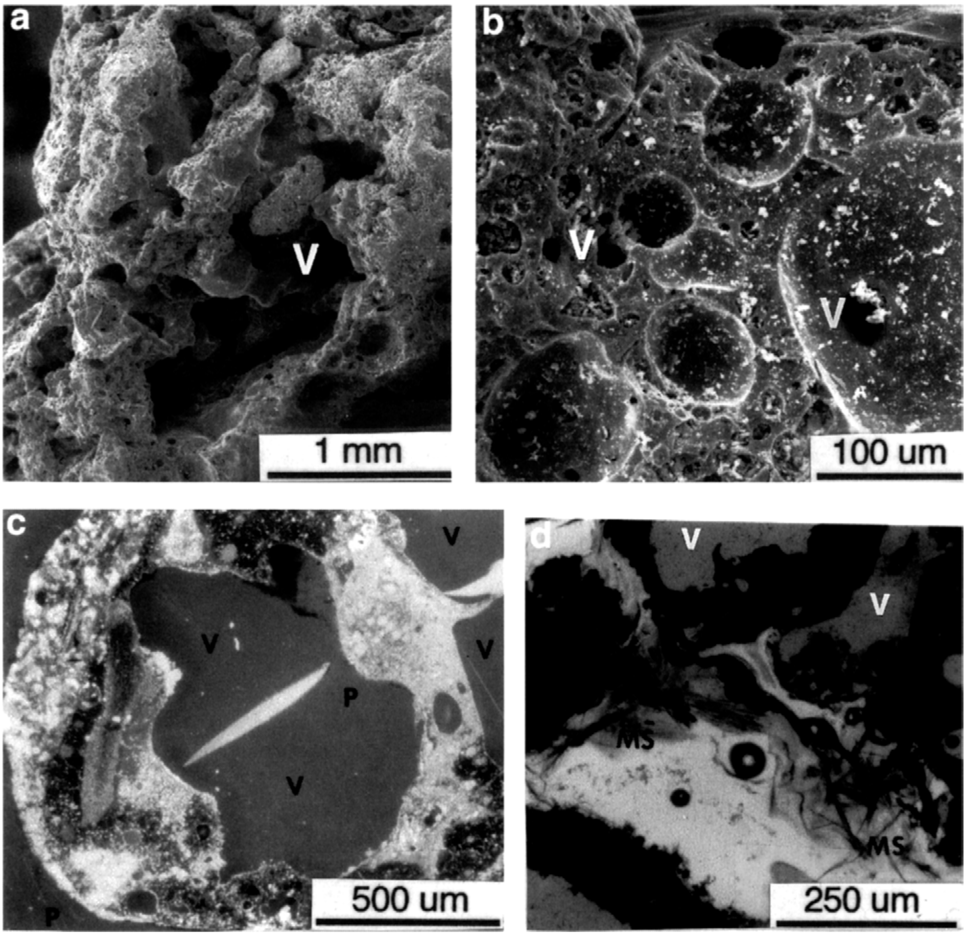


Table 9.16
Bottom Ash Surface Area

Country	Facility	BET Surface Area m^2/g	Pore Diameter[a] μm	Reference
United States	RDF[b]	4.605	-	Gardner, 1991
	PRF[b]	3.286	0.0947	Gardner, 1991
	RDF[b]	9.469	0.0786	Gardner, 1991
	RK-MB[b]	28.184	2.117	Gardner, 1991
	Unknown	9.4-46.3	-	Theis & Gardner, 1990
	MB[b]	3.2	0.0342	Kosson et al., 1992

[a] Mercury porosimetry.

[b] RDF=Refuse-Derived Fuel, PRF=Processed Refuse-Derived Fuel, RK=Rotary Kiln, MB=Mass Burn

In comparing the petrographic thin sections of bottom ash with the surface area and porosimetry data provided in Table 9.16, it is clear that the internal porosity that is connected to the exterior accounts for a great deal of the surface area measured by nitrogen BET absorption isotherms. Compared to most aggregates, bottom ash is considered to be a light-weight porous aggregate with more angularity and more surface roughness and textures than many traditional aggregates.

9.2.2 Mineralogy

The mineralogical characteristics of bottom ash play a very important role in the leaching behaviour of bottom ash. It is estimated that bottom ash contains numerous mineral phases. Such diversity complicates our understanding of the leaching behaviour of bottom ash and more research needs to be conducted on the role of mineralogy in bottom ash aging and strength development. Nevertheless, there are at least four studies that have been conducted that have examined the mineralogy of bottom ash. The studies have been conducted by Stämpfli (1992), Vehlow et al. (1992), Kirby and Rimstidt (1993) and Eighmy et al. (1994). All four of these studies have used rigorous procedures employing x-ray powder diffraction (XRPD) and other methods as precise procedures for estimating the nature of the mineral phases.

Stämpfli (1992) has examined bottom ash for the presence of those mineral phases that are associated with strength development as bottom ash ages. Stämpfli used XRPD to determine the mineralogy. Minerals identified include SiO_2, $CaCO_3$, Fe_3O_4, Fe_2O_3, Fe, FeO, $Ca_2Al(OH)_7{\bullet}6.5\,H_2O$, $Na_2Si_2O_5$, and $CaSO_4$. Others are shown in Table 9.17.

Table 9.17
Mineral Phases in Bottom Ash (in relative order of decreasing abundance)

Stämpfli (1992)[b]	Vehlow et al., (1992)[c]	Kirby and Rimstidt (1993)[d]	Eighmy et al. (1994)[e]
SiO_2	Fe_3O_4	SiO_2	$Ca_2Al_2SiO_7$
$CaCO_3$	SiO_2	$CaSO_4 \bullet 2H_2O$	$MgCa_2Si_2O_7$
Fe_3O_4	$(Ca,Na)_2(Al,Mg)(Si,Al)_2O_7$	$3(Al_2O_3) \bullet 2(SiO_2)$ TiO_2	Fe_3O_4
Fe_2O_3	$CaCO_3$	Fe_2O_3	$FeAl_2O_4$
Fe^0	$KAlSi_3O_8$	FeO	SiO_2
FeO	$NaAlSi_3O_8$	$CaSO_4$	$Ca_3(PO_4)_2$
$Ca_2Al(OH)_7 \bullet 6.5H_2O$	$CaAl_2Si_2O_8$	KCl	Fe_2O_3
$Na_2Si_2O_5$	$FeCr_2O_4$	NaCl	$CaSO_4$
$CaSO_4$	$Ca(Mg,Fe)Si_2O_6$		CaO
$(Ca,Na)(Al,Si)_2Si_8$	Fe_2SiO_4		$Al(OH)_3$
$NaAlSi_3O_8$	Cr_2O_3		NaCl
	Fe_2O_3		$ZnCl_2$
	$CaMgSiO_4$		$NaAlSi_3O_8$
	Al_2O_3		Al_2SiO_5
	$Ca(OH)_2$		TiO_2
	$CaSO_4$		

[b] Based on XRPD
[c] Based on petrography and XRPD
[d] Based on XRPD
[e] Based on petrography, XRPD, XPS, SEM/XRM

Vehlow et al. (1992) have conducted extensive characterisations of bottom ashes from three facilities in Germany. They used XRPD and petrography. Data are presented in Table 9.17. The principle phases found in ash from the German facilities are glass, magnetite, quartz, melilite and feldspar. A number of other minor phases were also identified. Agreement was seen in the relative presence of major phases amongst the three facilities. Vehlow et al. (1992) also looked at aging effects.

Kirby and Rimstidt (1993) studied bottom ashes containing small quantities of fly ash. They used XRPD as well. Principle minerals include (% abundance) Fe_2O_3 (3.7%), $CaCO_3$ (3.5%), NaCl (0.5%), SiO_2 (2.3%), magnetic spinel (3.5%), TiO_2 (1.1%), and $CaSO_4 \bullet 2H_2O$ (1.8%). The majority of the non-LOI mass of the sample was amorphous glass and minerals present below the detection limit for XRPD. Table 9.17 provides further information.

Eighmy et al. (1992) examined the characteristics of bottom ash using XRPD, petrography, SEM/XRM and surface microanalytical techniques for samples from a U.S.

facility. The bottom ashes were ground and separated using magnetic and density gradient separation procedures. Table 9.17 provides a summary of the data. Many of the phases found in the U.S. bottom ashes are similar to the ones identified by the other studies.

9.2.3 Alkalinity

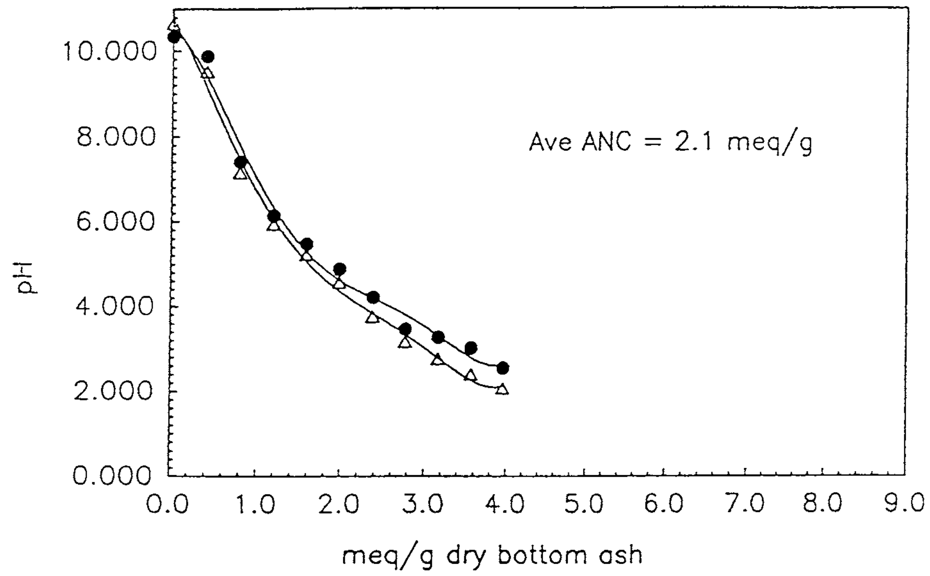
The buffer capacity of bottom ash is an important component in the leaching characteristics of bottom ashes. The acid neutralising capacity of the residue is a measure of how many milliequivalents of nitric acid are required to reduce the pH of one gram of residue to a value of 4.3. The endpoint of the titration can vary. Some researchers use a value of 7.0, while others use the more traditional carbonate alkalinity endpoint. To put this measure into perspective, one gram of residue would need to be leached with 45 litres of acidic precipitation to reduce the pH from 12.0 to 7.0. Table 9.18 provides some information on the acid neutralising capacity as well as the initial pH or the inherent pH of bottom ashes for samples collected from Canadian and U.S. facilities. Typically, bottom ash has an initial pH ranging from 10.5 to about 12.2. This is in part due to the presence of calcium hydroxides produced from CaO hydrolysis in the bottom ash. The acid neutralising capacity of bottom ash ranges from about 1.2 to 4.1 milliequivalents per gram. This means that bottom ash is reasonably well-buffered. Such buffering capacity indicates that bottom ash can moderately resist changes in pH.

Table 9.18
Bottom Ash pH and Acid Neutralising Capacity

Country	Facility	Initial pH	ANC, meq/g	Reference
Canada	LVH	10.20	3.05	Sawell et al., 1989b
	SWARU	-	4.11	Sawell et al., 1989a
	QUC	11.39	2.15	Sawell and Constable, 1988
United States	Concord, NH	10.5-12.2	1.2-3.0	Eighmy et al., 1992

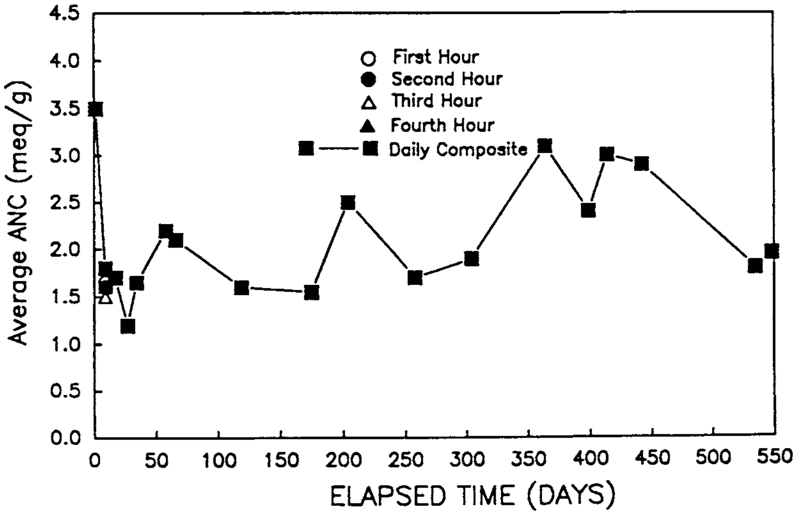
Figure 9.17 provides a typical titration curve for bottom ash. The data indicate that there are a number of locations in the titration curve where a slight degree of buffering takes place. These buffers tend to occur at a pH of around 10, 8 and 5. Such locations for buffers are attributable to the carbonate system. Figure 9.18 shows the change of botom ash acid neutralising capacity as a function of time for bottom ashes collected from the Concord facility (Eighmy et al. 1992). The acid neutralising capacity is relatively variable over time.

Figure 9.17 Bottom Ash Titration Curve



After Eighmy et al., 1992

Figure 9.18 Bottom Ash ANC as a Function of Time



After Eighmy et al., 1992

9.2.4 Influence of Combustor Type and Operation on Bottom Ash Surface Area, Mineralogy and Alkalinity

There is not a great deal of information available on the influence of combustor type and operation on the bottom ash particle morphology and mineralogy. Some of the data presented in Table 9.16 on bottom ash surface area suggests that newer mass burn facilities that burn at higher temperatures produce bottom ashes of higher relative surface areas. This may be a function of the quenching system and the degree of gas trapping that occurs when bottom ash slag is rapidly cooled.

As shown in Figure 9.19, two-stage bottom ash has less soluble mineral phases than mass burn or RDF systems. Using total dissolved solids as a measure of the presence of soluble mineral phases, two-stage systems are lower. This is believed to be because of poorer burnout and less complete oxidation of organics in the system.

As shown in Figure 9.20, the pH of two-stage bottom ash is generally lower than that of mass burn or RDF systems. This is believed to be due to the less efficient degree of oxidation of organic matter, the relatively low amounts of metal oxides and the reduced likelihood of forming alkaline hydroxides from oxide phases.

9.2.5 Influence of Aging on Bottom Ash Surface Area, Mineralogy and Alkalinity

At present there are four studies that have evaluated the influence of aging on bottom ash mineralogy. The first study is by Stämpfli (1992). As shown in Figure 9.21, x-ray powder diffraction traces of fresh and aged ashes from the Horgen facility in Switzerland suggest that some transformations occur during a four-month aging process. Stämpfli notes that certain mineral phases appeared in the aged residues. These include the minerals $CaSO_4 \cdot 2H_2O$ (gypsum), $Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$ (ettringite), $Na_2Si_2O_5$ and $Ca_2Al(OH)_7 \cdot 6.5\ H_2O$. The former two are related to strength development.

The work by Vehlow et al. (1992) suggests that aging does not drastically transform major mineral phases in bottom ash. The aging phenomenon was examined at three- and six-month increments. The data suggests that some mineral phases disappear with time; however, these mineral phases tend to be minor phases in the residues. The phases that tend to disappear with aging appear to be the phases $FeCr_2O_4$ (chromite), $Ca(Mg,Fe)Si_2O_6$ (diopside) and possibly $Ca(Mg,Fe,Al)(Si,Al)_2O_6$ (augite).

Zevenbergen et al. (1993) have identified a clay-like structure that forms when glassy phases in bottom ash are weathered. An illite-like 10 Å basal spacing in a weathered rim region was observed. The presence of such a mineral can increase the ability of bottom ash to retain metals that can ion-exchange onto clay surfaces.

Figure 9.19 Bottom Ash Total Dissolveable Solids as a Function of Combustor Type

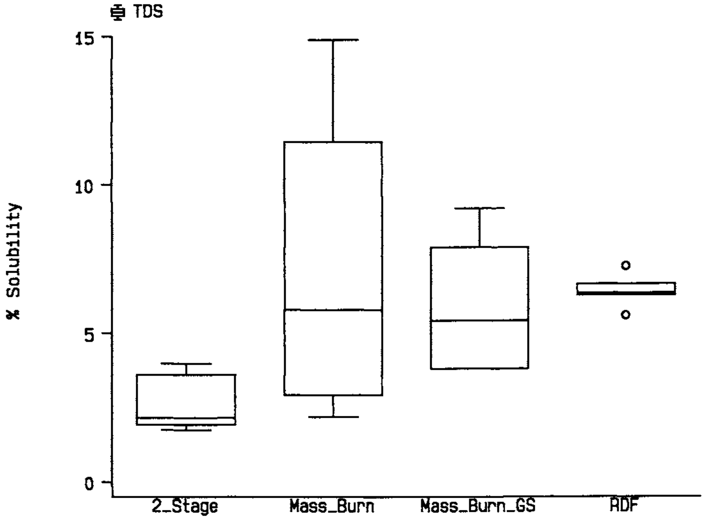


Figure 9.20 Bottom Ash pH as a Function of Combustor Type

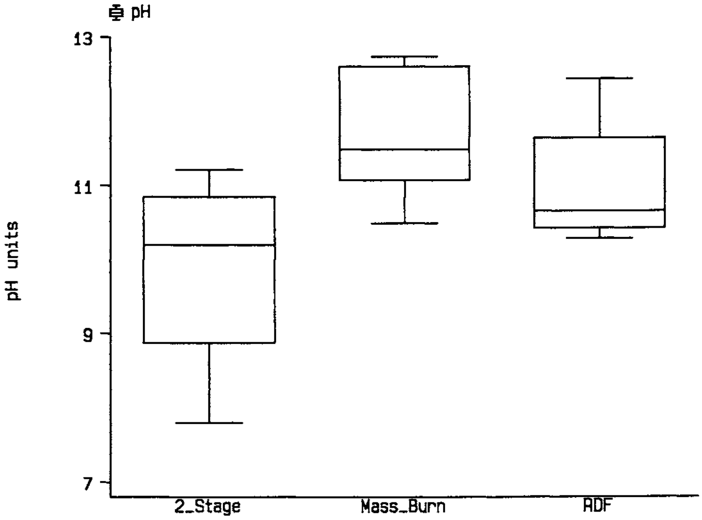
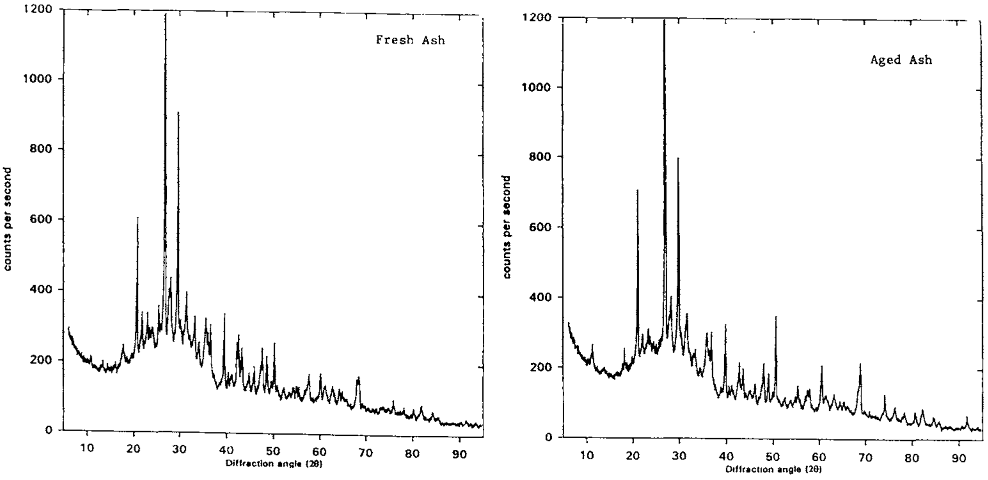


Figure 9.21 XRPD Diffractograms of Changes in Mineral Phases in Bottom Ash as a Function of Aging



After Stämpfli, 1992

Kluge et al. (1981) documented hydrogen gas evolution from road sub-bases made of bottom ash. The bottom ash aged *in situ*. During aging, hydrogen evolution caused cracking and blistering of the standard asphalt wearing course. Gas analyses obtained from blisters revealed hydrogen gas. The authors speculated that the following redox reaction was occurring:

$$2\ Al^{\circ} + 6H_2O \rightarrow 2\ Al(OH)_3(s) + 3H_2(g) \tag{9.1}$$

They hypothesise that other metallic components with valence states of zero (copper, zinc) could also promote similar redox reactions that promote hydrogen gas evolution.

9.3 INORGANIC CHARACTERISTICS OF BOTTOM ASH

Elemental distribution in bottom ash plays a very important role in the chemical behaviour of bottom ash. The chemical makeup of bottom ash also plays an important role in the physical and mineralogical characteristics.

9.3.1 Elements Present in Bottom Ash

The relative partitioning of elements into bottom ash is dependent on the chemical makeup of the MSW feed to the incinerator, the volatility of the element, the type of incinerator and grate system used to combust the waste, and the operation of the combustion system. These processes are presented in Chapters 3 and 8. Typically, over fifty elements can be identified in bottom ash using total compositional analytical methods. Some elements are present as major constituents (>10,000 mg/kg), some are present as minor constituents (>1,000 but <10,000 mg/kg) and most are present as trace constituents (<1,000 mg/kg). As shown in Table 9.19, when the entire range of concentration of elements in bottom ash is compared to typical constituents in either the lithosphere or in soils, it is apparent that some of the major matrix elements in bottom ash are very similar. The data provided in Table 9.19 (adapted from Lindsey, 1979) show that a number of the trace constituents in bottom ash are relatively enriched. Nevertheless, the composition of elements in bottom ash is for the most part comparable to those materials found in the lithosphere or soils.

Table 9.1 provides information on the incineration facilities within the various countries that generated the bottom ash that was evaluated in this section of the chapter. Many of the samples that were collected in each of the studies contain either grate siftings or economiser ash; however, the data that is to be presented here suggests that there is still similarity in the composition of bottom ash within each country, particularly for less volatile, lithophilic elements.

The composition of bottom ash has been broken down into various defining categories. The categories include major matrix elements, minor matrix elements, other minor elements, trace elements including oxyanionic elements, other trace elements, elements related to biogeochemical cycling and exotic elements, lanthanides and actinides. The designation of major, minor and trace descriptors is based on whether or not the concentration of the element is typically present at greater than 10,000 mg/kg (major), at concentrations ranging between 1,000 to 10,000 mg/kg (minor), and elements present at concentrations less than 1,000 mg/kg (trace). These designations by concentration are somewhat arbitrary but useful. It should also be noted here that all of the information provided on element concentration is based on the analysis of bottom ash using total quantification techniques. Such techniques include the use of neutron activation analysis or total digestion, followed by some spectrophotometric quantification. Therefore, the data available world-wide on bottom ash is rather limited because not all researchers have used total compositional analysis. In this chapter, it was felt that it was very important to only look at total composition. Many of the other analytical techniques that are based on partial analysis tend to recover only 50 or 60% of the element in the material and are not considered to be total compositional analyses.

Table 9.19
Lithosphere, Soil and Bottom Ash Composition

Element	Content in Lithosphere (ppm)[a]	Common Range for Soils (ppm)[a]	Ave for Soils (ppm)[a]	Range in Bottom Ash World-Wide
Ag	0.007	0.001-5	0.005	0.29-36.9
Al	81,000	10,000-300,000	71,000	21,900-72,800
As	5	1-50	5	0.12-189
Au	-	-	-	<0.20
B	10	2-100	10	38-510
Ba	430	100-3,000	430	400-3,000
Be	2.8	0.1-40	6	-
Br	2.5	1-10	5	1.4-150.2
C	950		20,000	10,000-60,000
Ca	36,000	7,000-500,000	13,700	370-123,000
Cd	0.2	0.01-0.70	0.06	0.3-70.5
Cl	500	20-900	100	800-4,190
Co	40	1-40	8	6-350
Cr	200	1-1,000	100	23-3,170
Cs	3.2	0.3-25	6	1.0-2.0
Cu	70	2-100	30	190-8,240
F	625	10-4,000	200	200-1,100
Fe	51,000	7,000-550,000	38,000	4,120-150,000
Ga	15	5-70	14	10
Ge	7	1-50	1	-
Hg	0.1	0.01-0.3	0.03	0.02-7.75
I	0.3	0.1-40	5	2-10
K	26,000	400-30,000	8,300	750-16,000
La	18	1-5,000	30	2-20
Li	65	5-200	20	-
Mg	21,000	600-6,000	5,000	400-26,000
Mn	900	20-3,000	600	83-2,400
Mo	2.30	0.2-5	2	2.5-276
N	-	200-4,000	1,400	110-900
Na	28,000	750-7,500	6,300	2,870-42,000
Ni	100	5-500	40	7-4,280
O	465,000		490,000	400,000-500,000
P	1,200	200-5,000	600	1,400-6,400
Pb	16	2-200	10	98-13,700
Rb	280	50-500	10	40-50
S	600	30-10,000	700	1,000-5,000
Sc	5	5-50	7	3-6
Sb	-	-	-	10-432
Se	0.09	0.1-2	0.3	0.05-10.0
Si	276,000	230,000-350,000	320,000	91,000-308,000
Sn	40	2-200	10	2-380
Sr	150	50-1,000	200	85-1,000
Ti	6,000	1,000-10,000	4,000	2,600-9,500
V	150	20-500	100	20-122
Y		25-250	50	10
Zn	80	10-300	50	613-7,770
Zr	220	60-2,000	300	200

Lindsay, 1979

9.3.2 Major Matrix Elements (> 10,000 mg/kg): O,Si,Fe,Ca,Al,Na,K,C

Figure 9.22 is a grouping of box plots depicting the concentration of the major matrix elements in bottom ash by country. The box plot depicts all of the data that is available for each of the countries. The central box for each of the elements in each plot extends from the first quartile to the third quartile, with a horizontal line to indicate the median value. The first quartile denotes the twenty-fifth percentile, the median denotes the fiftieth percentile and the third quartile denotes the seventy-fifth percentile. The height of the box equals the interquartile range. Lines are sometimes drawn out from the quartiles to adjacent values, defined as those data points less than 1.5 times the interquartile range beyond the first or third quartiles. Values more than 1.5 times the interquartile range are considered to be outliers and are denoted by individual circles in each of the plots. The use of box plots allows the reader to compare the databases that are available for each of the countries. In this chapter, the interquartile range is used for comparative purposes. As can be seen in many of the plots presented in this section, many of the data have outliers that denote a positive skewness in the data. Such skewness means the data are not normally distributed. The use of box plots is therefore the most appropriate measure for comparing populations of data that are not normally distributed.

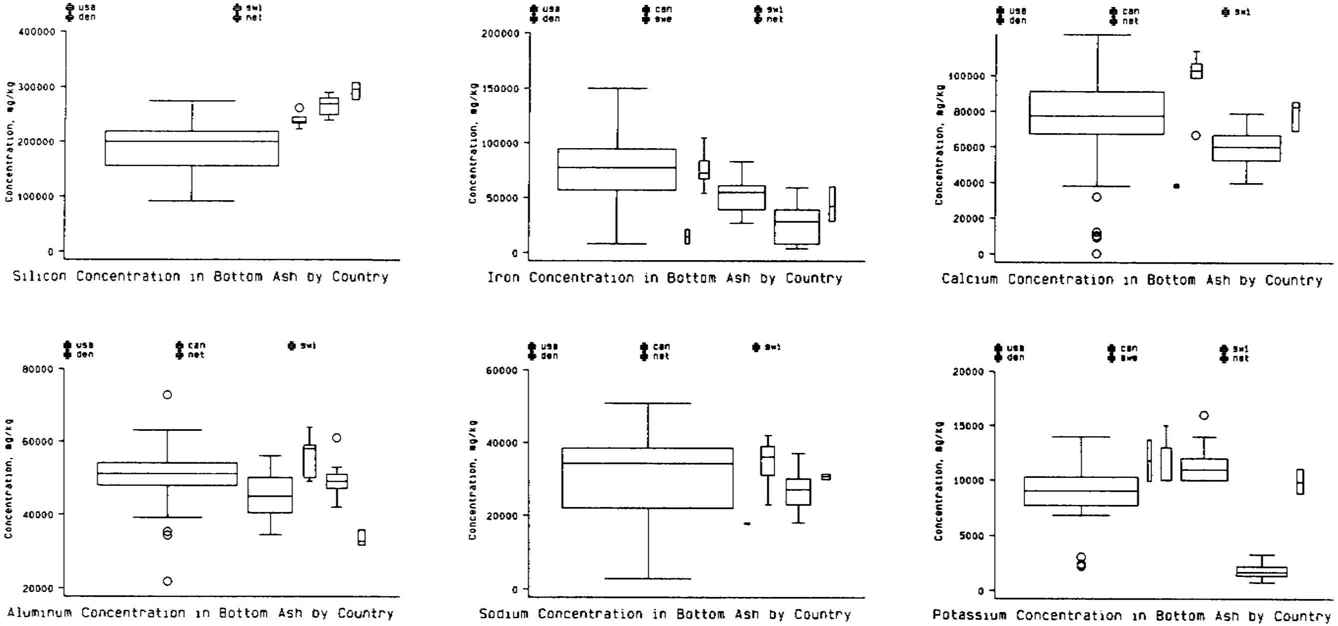
Oxygen is the most prevalent element in bottom ash. Its concentration is estimated to be between 300,000 to 500,000 mg/kg. It is present in bottom ash as oxides of silicon, iron, calcium, aluminum and carbon. Bottom ash concentrations are found to be similar to oxygen concentrations in either lithosphere or soil materials (see Table 9.19).

Silicon is present in bottom ash in concentrations ranging from 91,000 to 308,000 mg/kg. The data presented in Figure 9.22 show that there is a wide degree of variability in silicon concentration in the United States. Data from Switzerland, Denmark and the Netherlands are more closely grouped together at higher concentrations. Median values tend to be fairly close for each of these populations, with the United States, Switzerland, Denmark and the Netherlands having median values of 200,600, 237,000, 270,000 and 196,000 mg/kg respectively. The silicon concentration is similar to those observed in lithospheric and soil materials.

Iron is the next most abundant element in bottom ash. Typical values seen for bottom ash range from 4,120 to 150,000 mg/kg. Such concentrations are also similar to those found in soils and lithospheric materials. The range of data presented in the United States is found to be more variable. Data presented for Canada and the European countries tend to fall within the range presented for the United States. Median values by country are 79,000, 14,700, 73,000, 27,000, 28,150 and 42,400 mg/kg for the U.S., Canada, Switzerland, Denmark, Sweden and the Netherlands respectively.

Calcium is the next most abundant element in bottom ash. It is typically found at concentrations of 370 to 123,000 mg/kg. Such concentrations are similar to those observed in lithospheric and soil materials. As can be seen in Figure 9.22, median

Figure 9.22 Major Matrix Element Distribution by Country



Silicon Concentration in Bottom Ash by Country

Iron Concentration in Bottom Ash by Country

Calcium Concentration in Bottom Ash by Country

Aluminum Concentration in Bottom Ash by Country

Sodium Concentration in Bottom Ash by Country

Potassium Concentration in Bottom Ash by Country

The keys for each plot read left to right by line and correspond to the boxes moving left to right values for the United States, Canada, Switzerland, Denmark and the Netherlands are 77,700, 39,400, 103,000, 60,500, and 82,900 mg/kg respectively.

Aluminum is the next most abundant element in bottom ash. It is found in concentrations ranging from 21,900 to 72,800 mg/kg. It is similar in concentration to those seen in lithospheric and soil materials. Median values seen for the United States, Canada, Switzerland, Denmark and the Netherlands are 51,100, 45,000, 58,000, 49,000 and 32,900 mg/kg respectively.

Sodium is the next most abundant element in bottom ash. It is found in concentrations ranging from 2,870 to 42,000 mg/kg. Like many of the other major elements in bottom ash, its concentrations are also similar to those seen in lithospheric and soil materials. Median values observed for the United States, Canada, Switzerland, Denmark and the Netherlands are 34,300, 17,850, 36,000, 27,000, and 30,740 mg/kg respectively.

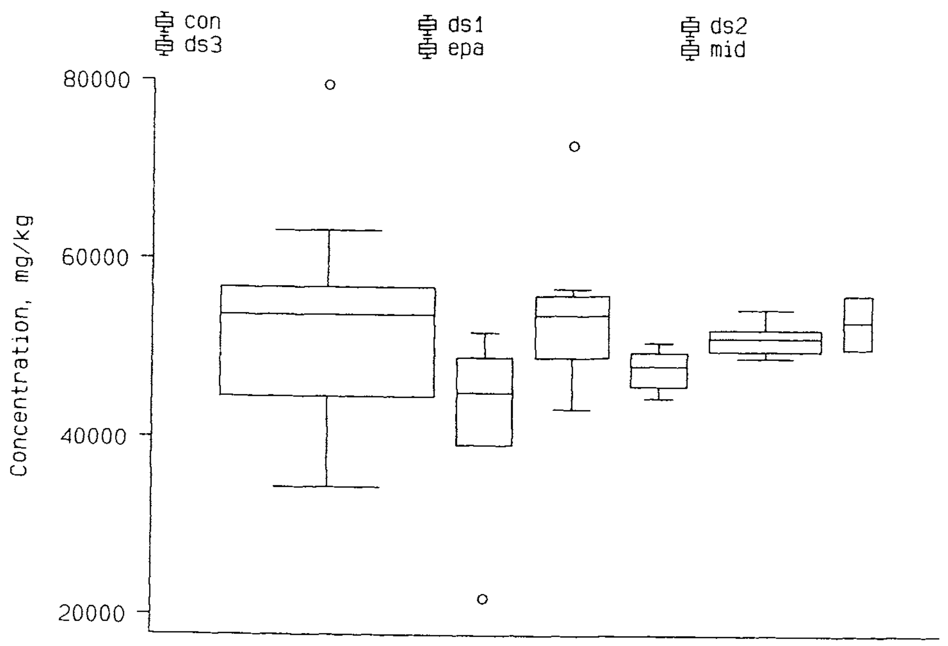
The next most abundant element in bottom ash is inorganic carbon. There is not a great deal of information available on the concentration of inorganic carbon in bottom ash. Data to date suggest that concentrations range between 20,000 to 40,000 mg/kg.

The last major matrix element that is present in bottom ash is potassium. Potassium is present in concentrations ranging from 750 to 16,000 mg/kg. Such concentrations are very similar to those seen in lithospheric and soil materials. Median values observed for the United States, Canada, Switzerland, Denmark, Sweden and the Netherlands are 9,000, 11,800, 13,000, 11,000, 1,685 and 9,880 mg/kg respectively.

As discussed in Chapter 8, many of these elements exhibit very low vapour pressures and are therefore not subjected to variations in combustion temperature. However, there is the possibility that the composition of the MSW feed going into the incinerator could alter the concentrations seen in bottom ash. As an example, Figure 9.23 is a plot of aluminum concentration in bottom ash for the various facilities in the United States. These facilities include the Concord facility in New Hampshire, the Dry Scrubber 1, Dry Scrubber 2 and Dry Scrubber 3 facilities, the EPA facility and the mid-Connecticut facility. As can be seen in Figure 9.23, the median values observed for aluminum in bottom ash from each of these facilities tends to be fairly close, ranging from 48,100 to 53,750 mg/kg. Such data suggest that for aluminum at least, there seems to be reasonably good agreement between different types of facilities with different types of MSW feed material for data presented for the United States.

Figure 9.24 shows how a major matrix element (aluminum) varies in bottom ash as a function of time. The data is presented for the Concord facility. Over the 1.5 year sampling time frame, the 18 sampling events show that the variation in total aluminum concentration is usually less than the variation seen within four consecutive hourly composites from any one sampling day. This data suggests that aluminum is a very conservative element in bottom ash. Most of the other major matrix elements exhibit similar behaviours.

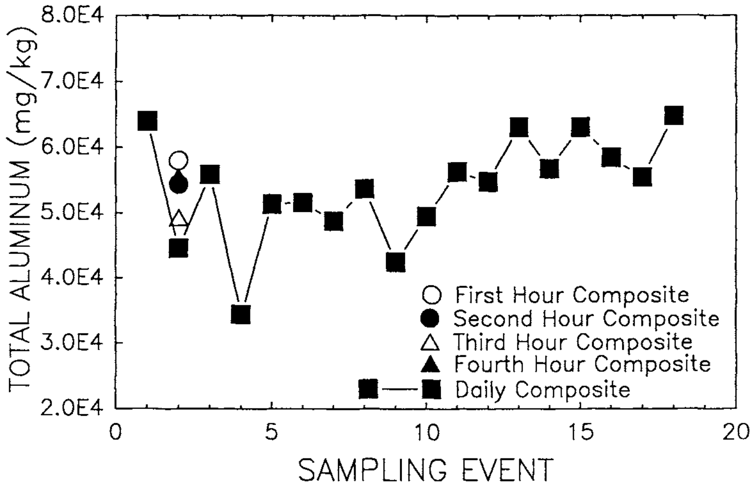
Figure 9.23 Major Matrix Element Distribution (Aluminum) within United States Facilities



Aluminum Concentrations in Bottom Ash From U.S. Facilities

Facility	n	min	max	mean	median
con	23	34,400	79,500	52,634	53,700
ds1	6	21,900	51,800	42,000	45,050
ds2	8	43,300	72,800	54,187	53,750
ds3	6	44,500	50,700	47,800	48,100
epa	12	49,000	54,400	51,208	51,200
midconn	3	50,000	56,000	53,000	53,000

Figure 9.24 Major Matrix Element Concentration (Aluminum) as a Function of Time



After Eighmy et al., 1992

9.3.3 Minor Matrix Elements (1,000 to 10,000 mg/kg): Mg, Ti, Cl, Mn, Ba

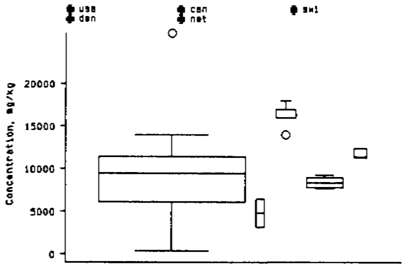
Figure 9.25 presents information on the minor matrix element distribution in bottom ash by country. Magnesium is the most prevalent minor matrix element in bottom ash. It ranges from 400 to 26,000 mg/kg. This range is similar to those seen in lithospheric and soil materials. Median values for the United States, Canada, Switzerland, Denmark and the Netherlands are 9,450, 4,850, 16,000, 8,400 and 11,400 mg/kg respectively. As can be seen in Figure 9.25, the magnesium concentration in bottom ashes by country does not exhibit variability. The variability seen within each of the countries is similar in the countries presented.

The next most abundant element is titanium. Titanium is present in concentrations ranging from 3,000 to 9,500 mg/kg. These are similar to lithophilic soils. Median values for the United States, Canada, Switzerland, Denmark and the Netherlands are 6,500, 8,000, 5,500, 4,100 and 4,150 mg/kg respectively.

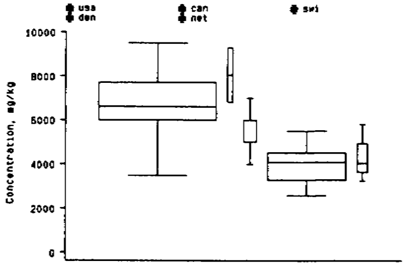
Chlorine is the next most abundant minor element in bottom ash (Figure 9.25). Median values for the United States, Switzerland, Denmark and the Netherlands are 2,100, 3,500, 1,800 and 1,900 mg/kg respectively. These values are enriched relative to soils.

Manganese is also a minor element in bottom ash. Data are reported for the United States, Canada, Denmark, Sweden and the Netherlands. Median values are all around 1,000 mg/kg. These are similar to soils.

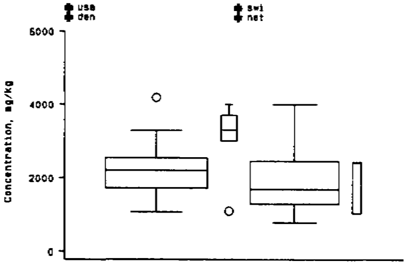
Figure 9.25 Minor Matrix Element Distribution by Country



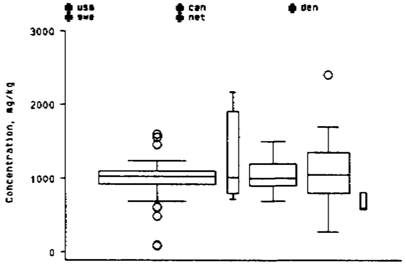
Magnesium Concentration in Bottom Ash by Country



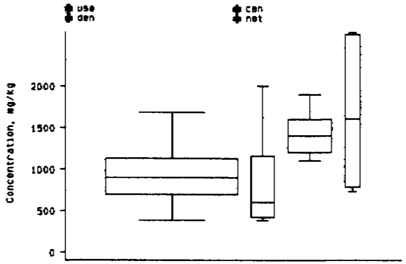
Titanium Concentration in Bottom Ash by Country



Chlorine Concentration in Bottom Ash by Country



Manganese Concentration in Bottom Ash by Country



Barium Concentration in Bottom Ash by Country

The next most abundant element in bottom ash in barium. Barium is present in concentrations ranging from 380 to 2,652 mg/kg. Such concentrations are similar to those seen for lithospheric or soil materials. The median values for the United States, Canada, Denmark and the Netherlands are 900, 600, 1400 and 1603 mg/kg respectively. As shown in Figure 9.25, the variability and range of data for each country are very similar.

It is interesting to compare the concentrations of barium in bottom ash from facilities within a single country. As shown in Figure 9.26, the concentration of barium is depicted in facilities from the United States. Six facilities are shown. As can be seen, the barium concentrations in bottom ash is remarkably similar for each of the six facilities.

It is also important to examine how variable the concentration of barium is within bottom ash collected at the same incineration facility over time. In Figure 9.27, the barium concentration in bottom ash is depicted for the Concord facility. The barium concentration over time tends to be as variable as the variation seen within four consecutive hourly sampling events from the one sampling day. This suggests that barium concentration can be somewhat variable in the process stream at the incinerator.

9.3.4 Other Minor Elements (1,000 to 10,000 mg/kg): Zn, Cu, Pb, Cr

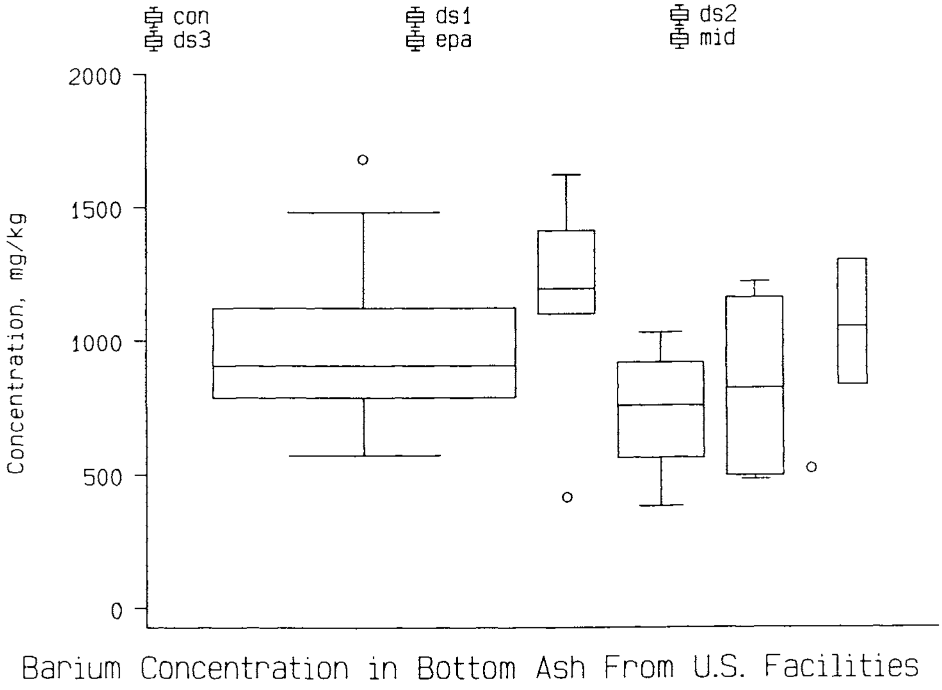
Other minor elements in bottom ash are depicted in Figure 9.28.

Zinc is a prevalent minor element in bottom ash. Its concentrations range from 613 to 7,770 mg/kg. Typically, it is enriched relative to lithosphere or soil materials. This is because zinc is widely used in manufactured goods. The median values seen for the United States, Canada, Germany, Denmark, Sweden and the Netherlands are 3,490, 2,420, 2,650, 2,200, 2,825 and 2,130 mg/kg respectively. As shown in Figure 9.28, the zinc concentration in bottom ash within the various countries is remarkably similar.

Another minor element in bottom ash is copper. Its concentrations range from 290 to 8,240 mg/kg. Like zinc, it is enriched relative to concentrations seen in lithospheric or soil materials. Copper is also widely used in manufactured goods. Median values observed for the United States, Canada, Germany, Denmark, Sweden and the Netherlands are 1,880, 2,286, 1,500, 2,500, 1,900 and 1,687 mg/kg respectively. As with zinc, the copper concentration in bottom ash is similar amongst the countries that are shown in Figure 9.28.

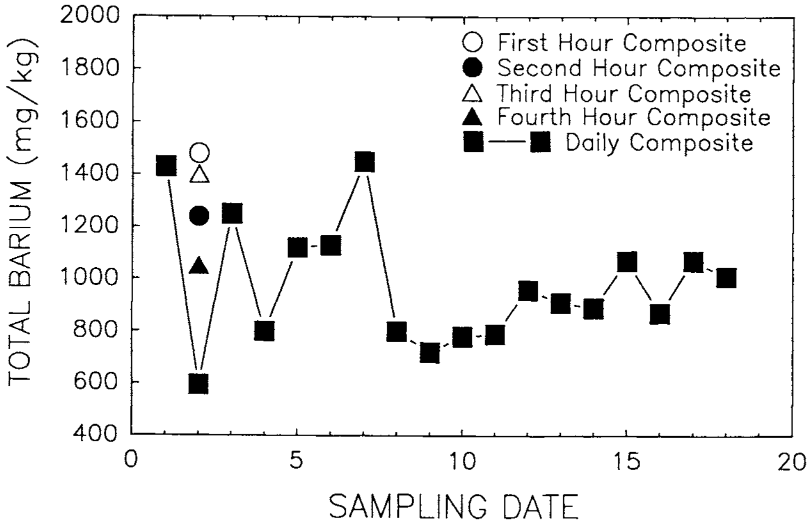
Another minor element is lead. Lead ranges in bottom ash from 98 to 13,700 mg/kg. It is very enriched relative to lithospheric and soil materials. Lead is also widely used in manufactured goods. It is a common soil contaminant near roadways. Median values for the United States, Canada, Germany, Denmark, Sweden and the

Figure 9.26 Minor Matrix Element Distribution (Barium) within United States Facilities



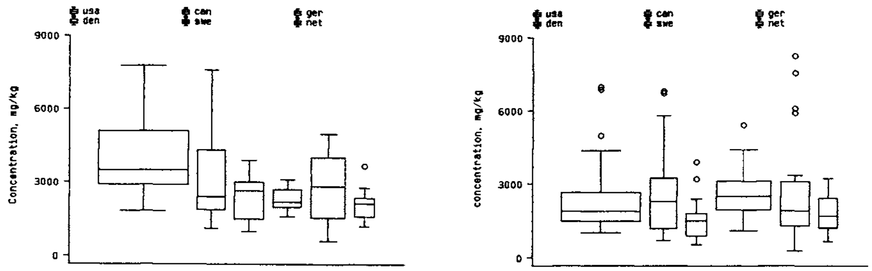
Facility	n	min	max	mean	median
con	32	570	1,680	981	905
ds1	6	417	1,620	1,156	1,195
ds2	9	383	1,030	719	754
ds3	6	481	1,220	832	818
sav	1	-	-	-	1,500
epa	1	-	-	-	520
mid	3	830	1,300	1,060	1,050

Figure 9.27 Minor Matrix Element Concentration (Barium) as a Function of Time



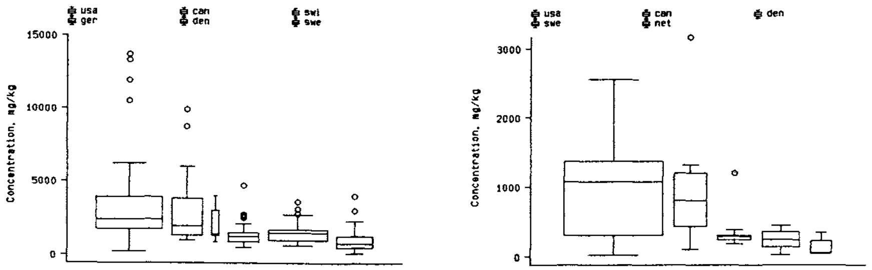
After Eighmy et al., 1992

Figure 9.28 Other Minor Element Distribution by Country



Zinc Concentration in Bottom Ash by Country

Copper Concentration in Bottom Ash by Country



Lead Concentration in Bottom Ash by Country

Chromium Concentration in Bottom Ash by Country

Netherlands are 2,400, 1,935, 1,250, 1,500, 780 and 1,295 mg/kg respectively. What is interesting to note in Figure 9.28 is that the median values for lead in bottom ash from each of the countries is very similar; however, almost all countries show outlier lead values that are high in concentration relative to the median values. Such outlier values are probably attributable to the analysis of small pieces of slag lead in the bottom ash. If the outliers are removed from the data bases, the data do show that their variation in lead concentrations in bottom ash are similar by country.

Chromium is another minor element in bottom ash. It ranges from 23 to 3,170 mg/kg. It is only slightly enriched relative to lithospheric or soil materials. Median values for the United States, Canada, Denmark, Sweden and the Netherlands are 1,072, 806, 290, 245 and 57 mg/kg respectively. As shown in Figure 9.28, the chromium concentration in bottom ash between countries is fairly uniform.

It is important again to evaluate how variable the other minor element concentrations can be in bottom ash from samples collected from facilities within the same country. As shown in Figure 9.29, the chromium concentration in bottom ashes from facilities in the United States exhibits a fair degree of variability. Such variability is probably attributable to the presence of automotive wastes in the MSW feed going to the incinerators. Facilities that utilise refuse processing tend to have less chromium in the bottom ash.

It is also important to evaluate how variable the chromium concentration can be in bottom ash as a function of time. As shown in Figure 9.30, the chromium concentration in the bottom ash from the Concord facility is remarkably uniform as a function of time.

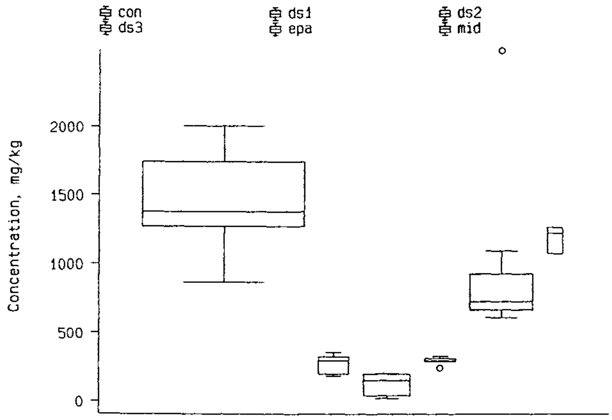
9.3.5 Other Trace Elements Including Oxyanionic Elements (<1,000 mg/kg): Sn, Sb, V, Mo, As, Se

The other trace elements, including oxyanionic elements, have been grouped together largely because of their behaviour during leaching; these elements tend to leach as oxyanions. Figure 9.31 shows box plots for how these elements are distributed in bottom ash by country.

Tin, which is not an oxyanion, ranges in concentration from 2 to 380 mg/kg. Its concentration is very similar to those seen in lithosphere or soil materials. Median values for the United States, Canada, Denmark and the Netherlands are 254, 10, 200 and 10 mg/kg respectively. As can be seen in Figure 9.31, the data for the United States and Denmark are remarkably similar in their distributions, but these two data populations differ from the data available for Canada and the Netherlands.

Antimony is the most abundant trace oxyanionic element in bottom ash. It is present in concentrations ranging from 10 to 432 mg/kg. It is enriched in bottom ash relative to its concentration in the lithosphere or in soils. Median values for the United States,

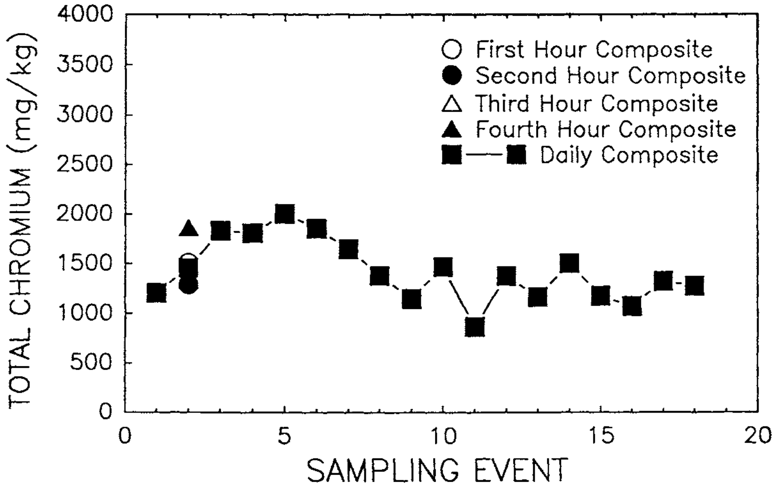
Figure 9.29 Other Minor Element Distribution by Country



Chromium Concentration in Bottom Ash From U.S. Facilities

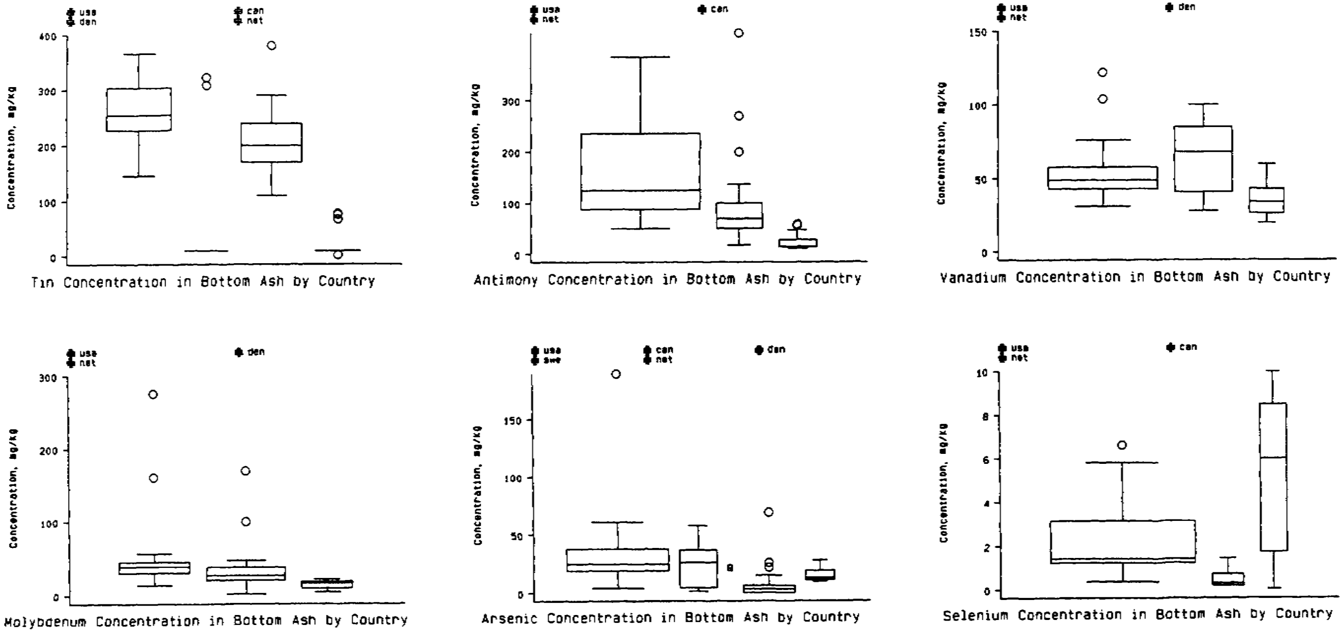
Facility	n	min	max	mean	median
Con	31	867	2,004	1,457	1,378
Ds1	6	185	358	277	298
ds2	9	23	205	130	153
ds3	6	245	329	295	297
epa	12	-	-	-	724
mid	3	1,070	1,260	1,183	1,220

Figure 9.30 Other Minor Element Concentration (Chromium) as a Function of Time



After Eighmy et al., 1992

Figure 9.31 Trace Oxyanionic Element Distribution by Country



Tin Concentration in Bottom Ash by Country

Antimony Concentration in Bottom Ash by Country

Vanadium Concentration in Bottom Ash by Country

Molybdenum Concentration in Bottom Ash by Country

Arsenic Concentration in Bottom Ash by Country

Selenium Concentration in Bottom Ash by Country

Canada and the Netherlands are 125, 69 and 15 mg/kg respectively. As shown in Figure 9.31, there is some variability between countries in the concentrations of antimony present in bottom ash.

Vanadium is the next most abundant trace oxyanionic element in bottom ash. It is found in concentrations ranging from 20 to 122 mg/kg. It is relatively difficult to recover this element from bottom ash. These concentrations tend to be lower than the concentrations found in the lithosphere or soils. Median values for the United States, Denmark and the Netherlands are 49, 68 and 34 mg/kg respectively. The concentrations of vanadium in bottom ash between countries is remarkably similar.

The next most abundant trace oxyanionic element is molybdenum. It is found in concentrations in bottom ash ranging from 2.5 to 276 mg/kg. It is enriched in bottom ash relative to concentrations seen in the lithosphere or soils. Median values for the United States, Denmark and the Netherlands are 39.5, 27.5 and 17.0 mg/kg respectively. As shown in Figure 9.31, concentration of molybdenum in bottom ash between countries is very similar.

The next most abundant trace oxyanionic element in bottom ash is arsenic. Typical concentrations range from 0.12 to 189 mg/kg. Such concentrations are slightly higher than those seen in the lithosphere or soils. Median values for the United States, Canada, Denmark, Sweden and the Netherlands are 25, 26.2, 21.5, 3.0 and 13.0 mg/kg respectively. The concentrations of arsenic in bottom ash are remarkably similar for the countries that are presented in the figure.

The next most abundant trace oxyanionic element in bottom ash is selenium. Typically selenium range in bottom ash from 0.05 to 10.0 mg/kg. These concentrations tend to be slightly enriched relative to lithospheric or soil materials. Median values for the United States, Canada and the Netherlands are 1.44, 0.30 and 6.00 mg/kg respectively.

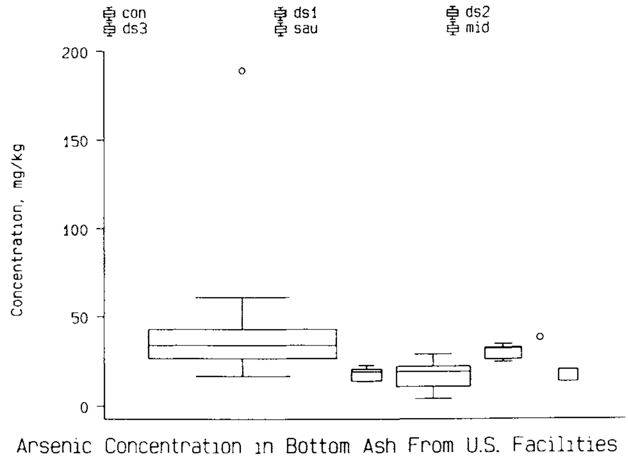
As shown in Figure 9.32, arsenic distributions in bottom ashes from facilities from the United States are similar. Median values tend to range from 19.1 to 38.0 mg/kg.

It is also important to understand how variable trace oxyanionic elements can be in bottom ash in process streams from an incinerator. As shown in Figure 9.33, arsenic concentrations in bottom ash are depicted for bottom ash produced at the Concord facility. The arsenic concentrations tend to exhibit some variation with time; the variation tends to be about the same as that seen in concentrations in four consecutive hourly samples from the one sampling day. The samples were collected over a 1.5 year period.

9.3.6 Other Trace Elements (<1,000 mg/kg): Sr, Ni, Co, Cd, Ag, Hg

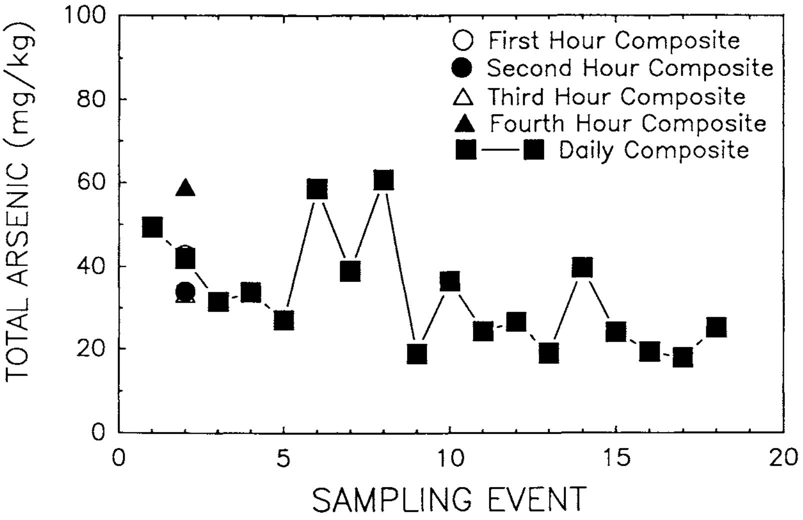
Figure 9.34 shows box plots for additional trace element distributions by country.

Figure 9.32 Trace Oxyanionic Element Distribution (Arsenic) Within the United States



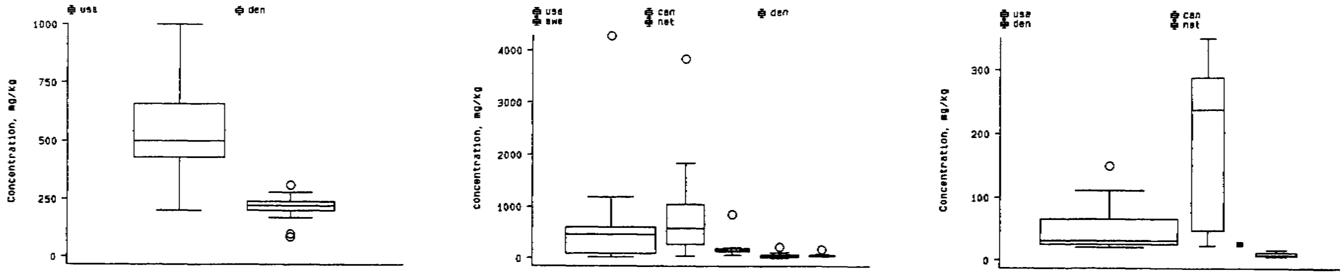
Facility	n	min	max	mean	median
con	31	16.7	189	39.53	33.90
ds1	5	13.7	20.5	17.98	19.10
ds2	12	4.0	28.8	17.13	19.20
ds3	6	24.5	34.5	30.21	31.85
Saugus	1	-	-	-	38.0
midconn	3	13.6	20.3	18.0	20.1

Figure 9.33 Trace Oxyanionic Element Concentration (Arsenic) as a Function of Time



After Eighmy et al., 1992

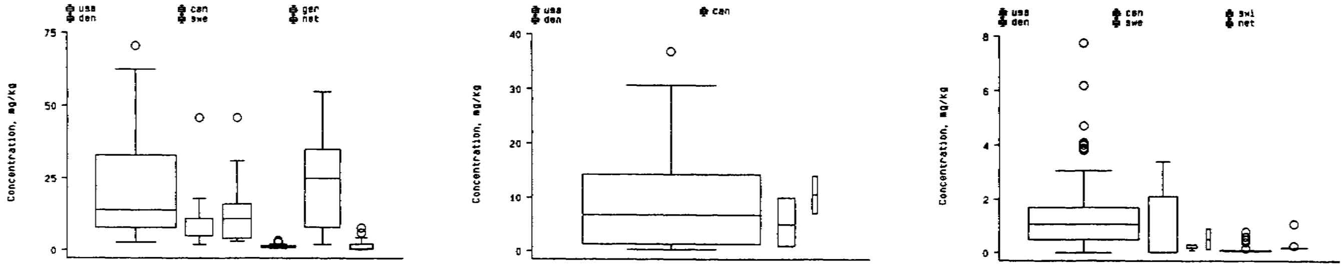
Figure 9.34 Other Trace Element Distribution by Country



Strontium Concentration in Bottom Ash by Country

Nickel Concentration in Bottom Ash by Country

Cobalt Concentration in Bottom Ash by Country



Cadmium Concentration in Bottom Ash by Country

Silver Concentration in Bottom Ash by Country

Mercury Concentration in Bottom Ash by Country

Strontium is present in bottom ash at concentrations ranging from 85 to 1,000 mg/kg. Such concentrations are similar to concentrations seen in lithospheric and soil materials. Median values for strontium in bottom ash for the United States and Denmark are 500 and 220 mg/kg respectively. As shown in Figure 9.34, the concentrations of strontium seem to be higher in the United States bottom ashes compared to those concentrations seen in Danish bottom ashes. At this time, no explanations can be provided for this phenomena.

Nickel is found in bottom ashes in concentrations of 7 to 4,280 mg/kg. Median values for the United States, Canada, Denmark, Sweden and the Netherlands are 470, 584, 155, 55.5 and 50.0 mg/kg, respectively. The concentrations of nickel in the North American countries tends to be higher than those seen for the European facilities.

Cobalt is found in bottom ash at concentrations ranging from 6 to 350 mg/kg. Values found in lithospheric and soil materials tend to be lower. Median values for the United States, Canada, Denmark and the Netherlands are 31.5, 238, 26.5 and 8.5 mg/kg respectively. The concentrations in Canadian facilities tends to be much higher than those observed in either the U.S., Danish or Dutch facilities.

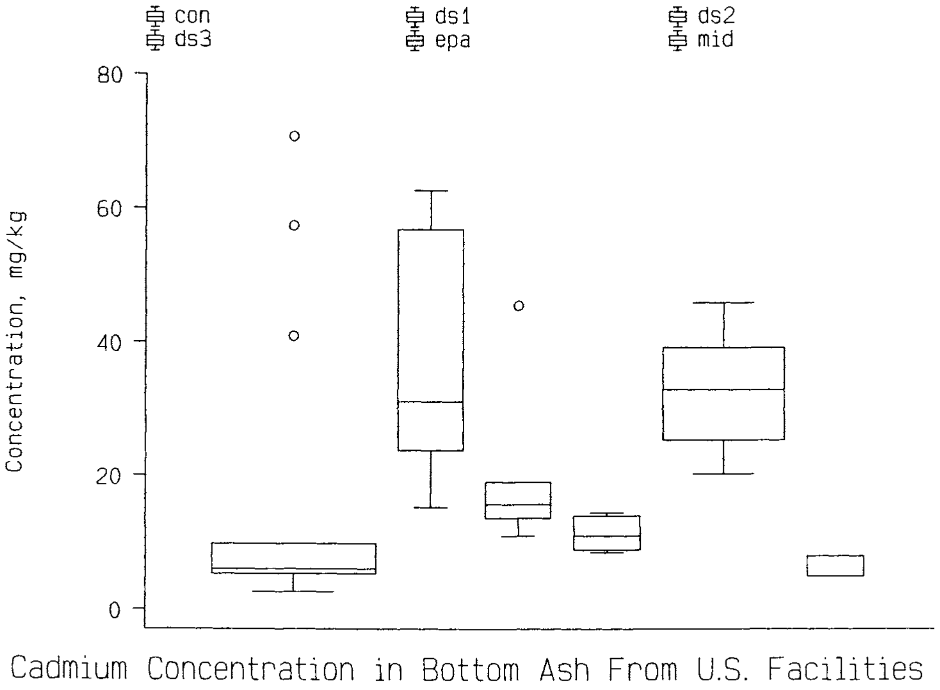
Cadmium is found in bottom ash at concentrations ranging from 0.3 to 70.5 mg/kg. Such concentrations are very enriched relative to lithospheric or soil materials. Median values for the United States, Canada, Germany, Denmark, Sweden and the Netherlands are 13.9, 5.0, 11.0, 1.3, 25.0 and 0.5 mg/kg respectively.

Silver concentrations range in bottom ash from 0.29 to 36.9 mg/kg. Such concentrations are very enriched relative to lithospheric or soil materials. Median values for the United States, Canada and Denmark are 6.75, 5.00 and 10.55 mg/kg respectively. As shown in Figure 9.34, the concentrations of silver in bottom ash is fairly similar between the three countries that are depicted.

Mercury concentrations in bottom ash range from 0.02 to 7.75 mg/kg. Such concentrations are much higher than those seen for lithospheric or soil materials. Median values for the United States, Canada, Switzerland, Denmark, Sweden and the Netherlands are 1.08, 0.02, 0.20, 0.52, 0.08 and 0.20 mg/kg respectively. As can be seen in Figure 9.34, the concentrations of mercury in North American facilities is much higher than those seen for facilities in Europe.

It is important to understand how the concentration of some of these additional trace elements can vary in bottom ash samples from facilities within the same country. As shown in Figure 9.35, the concentration of cadmium in bottom ashes from the United States facilities is found to be quite variable. At this time it is not certain as to why. It may be a function of both the waste composition that is being combusted and the temperature of combustion.

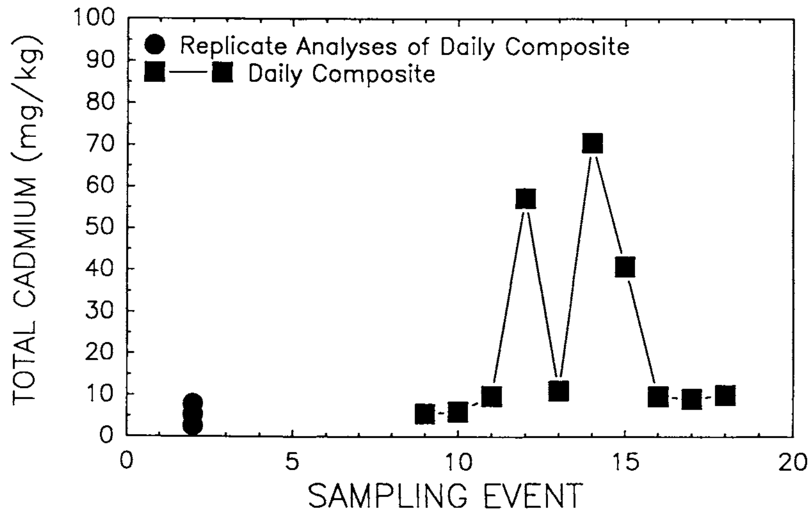
Figure 9.35 Other Trace Element Distribution (Cadmium) within United States Facilities



Facility	n	min	max	mean	median
con	15	2.62	70.57	16.15	6.06
ds1	6	15.2	62.5	36.7	31.1
ds2	6	11.0	45.4	20.0	15.6
ds3	6	8.5	14.4	11.28	11.0
epa	11	20.2	45.8	32.4	32.9
mid	5	5	8	6.2	5.0

It is also important to understand how variable trace elements can be in bottom ashes produced from the same facility over time. Cadmium has been selected as an example. As shown in Figure 9.36, cadmium can be quite variable in the bottom ash process stream over time. Sampling occurred at the Concord, New Hampshire facility over a 548-day period. It is not clear why cadmium is so variable in bottom ash. It may be due to waste stream effects and the fact that cadmium is a very volatile element.

Figure 9.36 Other Trace Element Concentrations (Cadmium) as a Function of Time



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9.3.7 Other Trace Elements Continued (<1,000 mg/kg): B, Br, F, I

Concentrations of some other trace elements in bottom ashes by country is depicted in box plots shown in Figure 9.37. Boron is found in concentrations ranging from 38 to 510 mg/kg. Such concentrations tend to be slightly enriched relative to lithospheric or soil materials. Median values for the United States and Canada are 140 and 171 mg/kg respectively. As shown in Figure 9.37, boron concentration is quite similar in bottom ashes from the United States and Canada.

Bromine is found in bottom ash in concentrations ranging from 1.4 to 150.2 mg/kg. Such concentrations are higher than those seen in lithospheric or soil materials. Median values for bromine in the United States and the Netherlands are 40.75 and 2.40 mg/kg respectively. There is a wide difference in concentrations of bromine between the United States and Dutch bottom ashes.

Fluorine is found in bottom ashes in concentrations ranging from 200 to 1,100 mg/kg. Such concentrations tend to be less than those seen in lithospheric or soil materials. Median values for Switzerland, Denmark and the Netherlands are 300, 500 and 385 mg/kg respectively. As shown in Figure 9.37, the concentrations between the three European countries is similar.

Iodine is also found in bottom ash. The data are very limited. he data suggests that iodine is present in concentrations of around 1,000 mg/kg.

9.3.8 Elements Related to Biogeochemical Cycles: C, S, P, N

Figure 9.38 shows distribution of elements by country for those elements related to biogeochemical cycling.

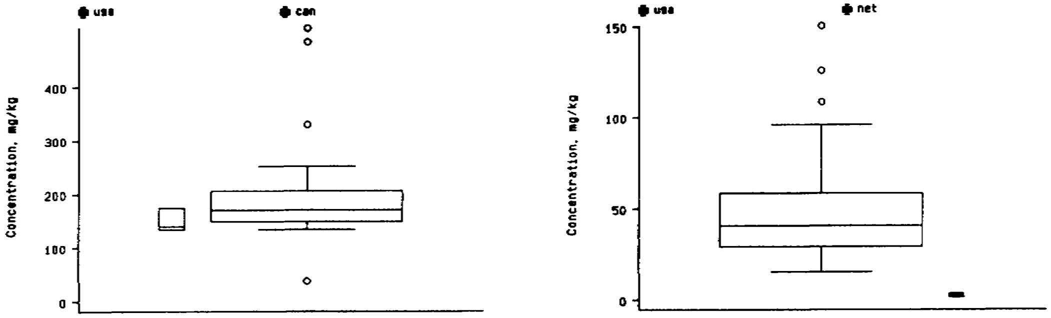
Organic carbon is the most prevalent element in bottom ash related to biogeochemical cycling. Very limited data are available on the concentrations of organic carbon in bottom ash. Those data that are available suggest that organic carbon is present in concentrations of 10,000 to 20,000 mg/kg though higher concentrations are possible.

Sulphur is the next most abundant element related to biogeochemical cycling in bottom ash. Sulfur is found in concentrations ranging from 1,000 to 5,000 mg/kg. Such concentrations are less than those typically seen in lithospheric or soil materials. The majority of the sulphur that is present in bottom ash is present as sulphate. Median values for sulphur in bottom ash for the United States, Canada, Switzerland and Denmark are 6,100, 4,070, 2,000 and 2,100 mg/kg respectively. As can be seen in Figure 9.38, the total sulphur concentrations in bottom ashes from around the world are fairly similar.

The next most abundant element in bottom ash relative to biogeochemical cycling is phosphorus. Phosphorus is found in concentrations ranging from 1,400 to 6,400 mg/kg. Such concentrations are similar to those seen in lithospheric and soil materials. Median values for the United States, Canada, Switzerland and Denmark are 2,900, 3,350, 5,000 and 3,450 mg/kg respectively. The total phosphorus concentrations in bottom ash are fairly similar between countries around the world.

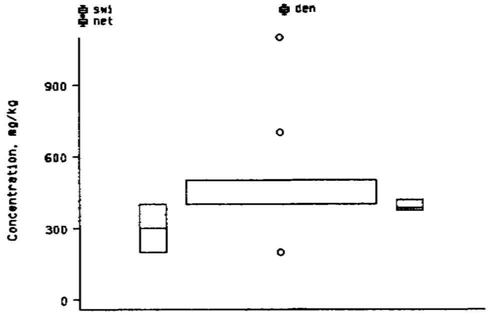
The next most abundant element in bottom ash relative to biogeochemical cycling is nitrogen. Nitrogen is found in concentrations ranging from 110 to 900 mg/kg. Such concentrations are less than those seen in lithospheric or soil materials. Median values for Switzerland and Denmark are 400 and 490 mg/kg respectively. As can be shown in Figure 9.38, such concentrations are similar between the two countries.

Figure 9.37 Other Trace Element Distributions by Country



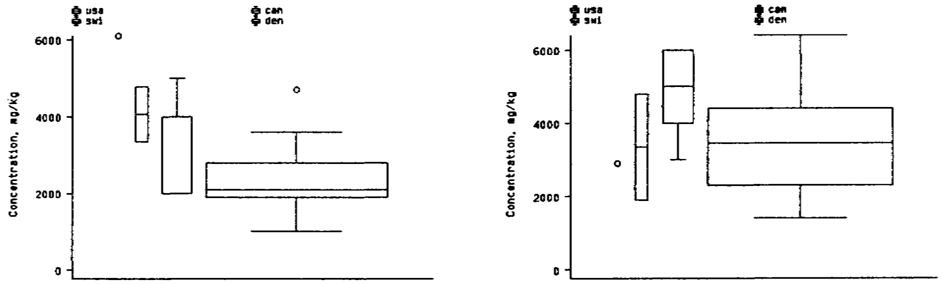
Boron Concentration in bottom Ash by Country

Bromine Concentration in Bottom Ash by Country



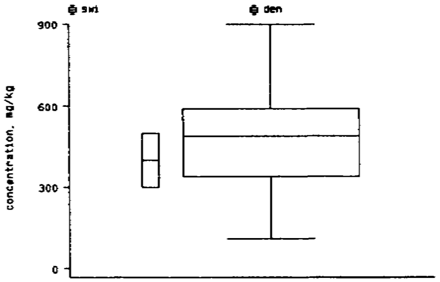
Fluorine Concentration in Bottom Ash by Country

Figure 9.38 Elemental Distributions by Country of Elements Related to Biogeochemical Cycling



Sulfur Concentration in Bottom Ash by Country

Phosphorus Concentration in Bottom Ash by Country



Nitrogen Concentration in Bottom Ash by Country

9.3.9 Exotic Elements, Lanthanides, Actinides

There are a number of exotic elements, lanthanides, and actinides that have been measured in bottom ash. As shown in Table 9.19, the elements scandium, rubidium, cesium, lanthanum, tantalum, gold and indium are found in bottom ashes at concentrations that are usually less than 10 mg/kg. There is very little information available on the concentrations of these elements in bottom ashes. Data are available from Eighmy et al. (1992). These exotic elements play a minor role in ash physical properties and chemistry. Nevertheless, these elements are present.

There are a number of lanthanide elements that are present in bottom ashes. These include cerium, neodymium, scandium, europium, terbium, tellurium, dysprosium, and ytterbium. These exotic elements are present in concentrations less than 1 mg/kg. They play a negligible role in ash characteristics.

Actinides are also present in bottom ash. Thorium and uranium are the two elements that have been found. Their concentrations tend to be less than 1 mg/kg. Like the lanthanides, these actinides play a negligible role in ash characterisation. They are not enriched relative to soils.

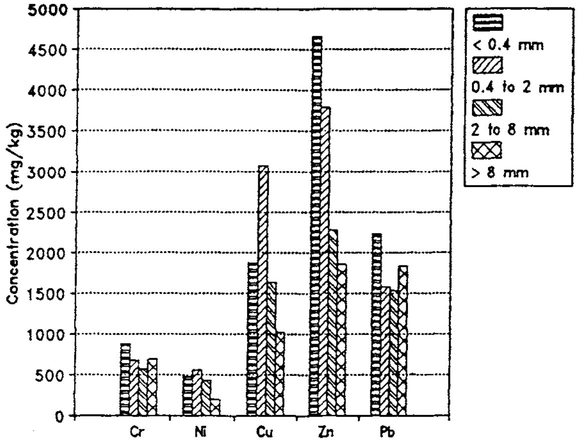
9.3.10 Isotopes

Some limited information is available on the presence of radioactive isotopes of elements in bottom ash. The data show that the levels seen in bottom ash are the same as those seen for natural soils. Data reported by van der Sloot (1992) show the following activities for ^{226}Ra, ^{228}Th, ^{228}Ra and ^{40}K, respectively (Bq/kg): 18.6, 15.2, 13.3 and 277. Soils have values of 10 to 40, 10 to 50, 10 to 50 and 200 to 500 for those same isotopes (Ackers et al. 1985).

9.3.11 Role of Particle Size in Element Distribution

Stegemann and Schneider (1991) have examined how copper, nickel, chromium, zinc and lead vary as a function of particle size (<0.4 mm, 0.4-2 mm, 2-8 mm, >8 mm). Zinc was the only element that exhibited enrichment as a function of decreasing particle size. Figure 9.39 presents the data. Conversely, data from the NITEP program (Sawell et al., 1990a), relative to the GVRD facility, do show that lead is enriched in the finer fractions (e.g. $\geq$ 1.0 mm to < 4.0 mm and the <1.0 mm fractions). The reason for the relative enrichment of certain metals in the fine fraction is not clear, though it may be related to how these metals, as pure solids, melt to form smaller particle sizes.

Figure 9.39 Element Distribution by Particle Size



After Stegemann and Schneider, 1991

9.3.12 Influence of Combustor Type and Operation on Bottom Ash Inorganic Characteristics

The NITEP and WASTE programs provide the best information to date on the influence of combustor type and operation on bottom ash inorganic composition. The NITEP program is noteworthy because of its comprehensive evaluation of a variety of combustor types and combustion conditions on ash quality (Sawell and Constable, 1993). The WASTE program is noteworthy because of its evaluation of the influence of MSW composition on bottom ash composition (WASTE Program, 1993).

Aluminum concentrations in bottom ashes are shown in box plots in Figure 9.40. Generally, the concentration is lower in two-stage bottom ashes, possibly because of the dilution effect from unburned material in the bottom ash.

Copper (Figure 9.41), nickel (Figure 9.42), zinc (Figure 9.43) and chromium (Figure 9.94) also show similar behaviours to that of aluminum. All of these elements have relatively high vapour pressures and would be expected to remain in the bottom ash fraction during combustion (see Chapter 8).

Elements that are much more volatile, such as cadmium, show a different behaviour than less volatile elements. Cadmium concentrations in bottom ashes are shown in Figure 9.45. The highest concentrations are found in bottom ashes with the lowest hearth temperatures. Thus, the two-stage bottom ashes have the highest levels. There is relatively close agreement amongst the samples from mass burn and RDF facilities.

Figure 9.40 Aluminum Concentration in Bottom Ashes and Grate Siftings as a Function of Combustor Type

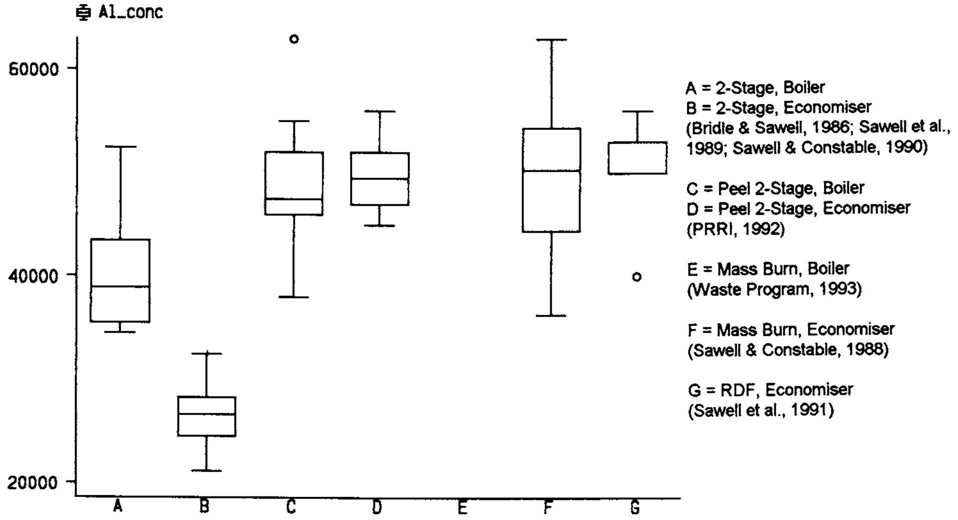


Figure 9.41 Copper Concentration in Bottom Ash and Grate Siftings as a Function of Combustor Type

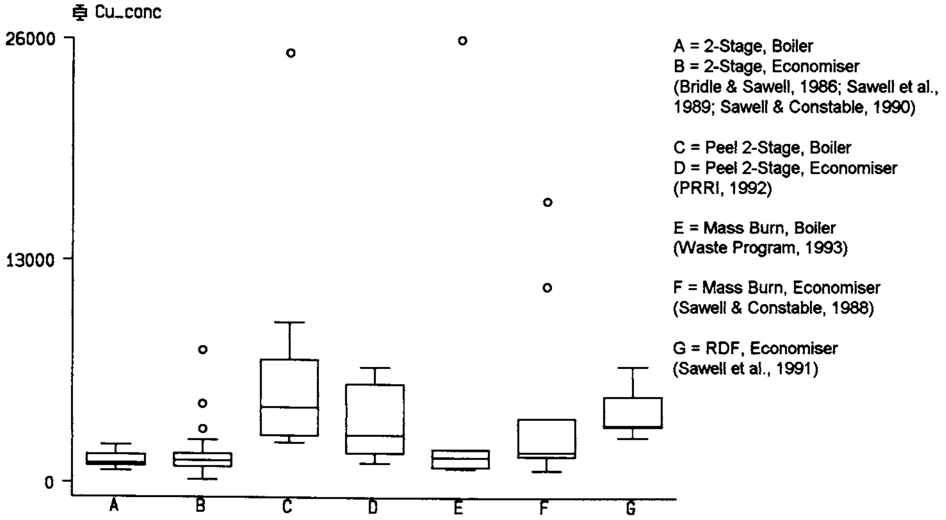


Figure 9.42 Nickel Concentration in Bottom Ashes and Grate Siftings as a Function of Combustor Type

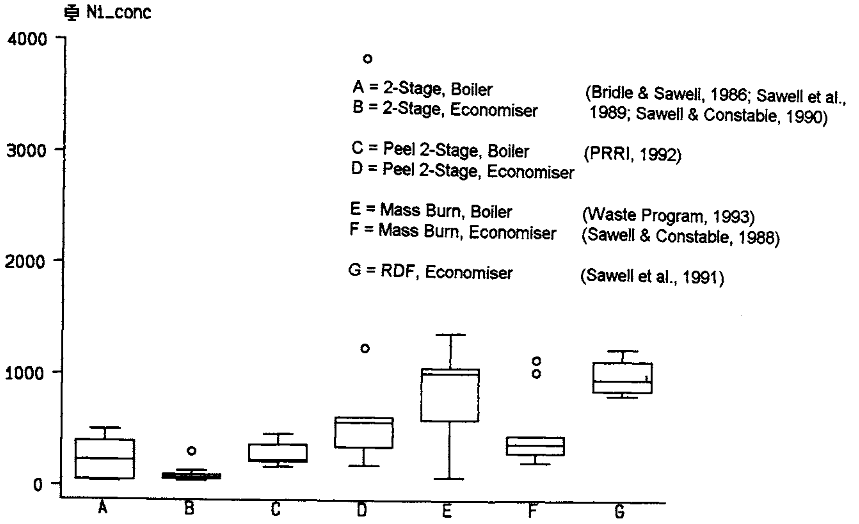


Figure 9.43 Zinc Concentration in Bottom Ash and Grate Siftings as a Function of Combustor Type

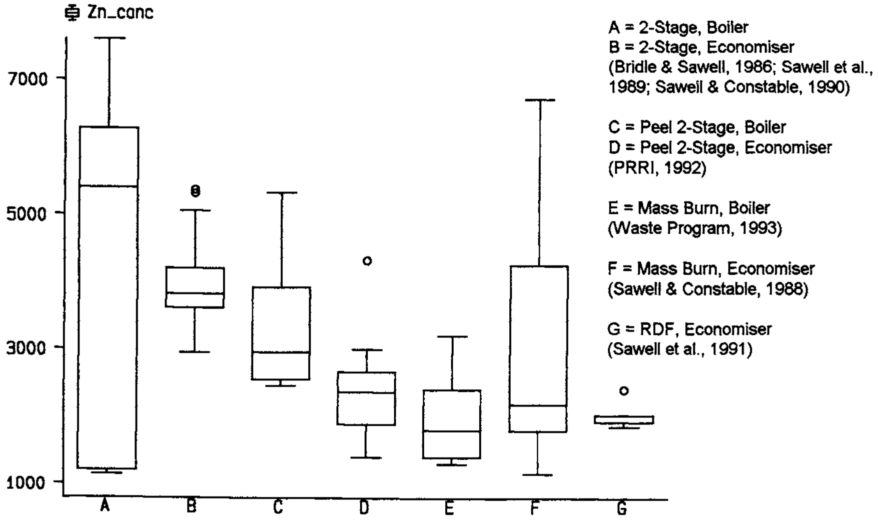


Figure 9.44 Chromium Concentration in Bottom Ashes and Grate Siftings as a Function of Combustor Type

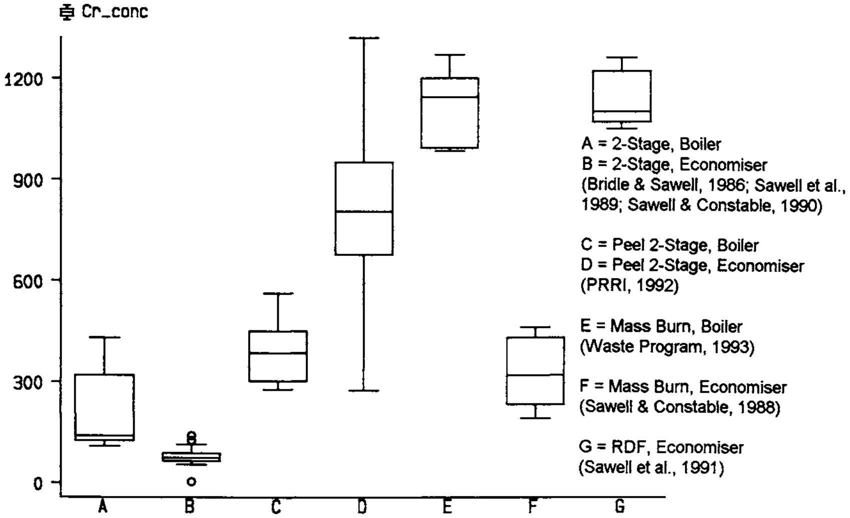
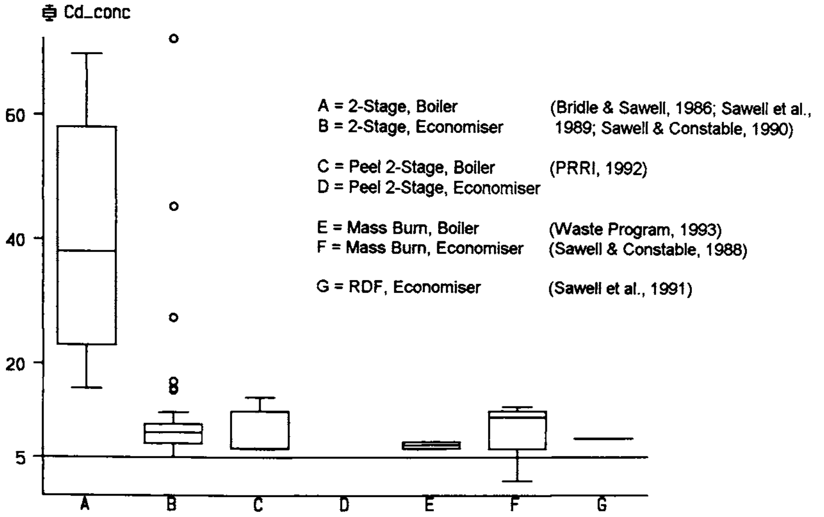
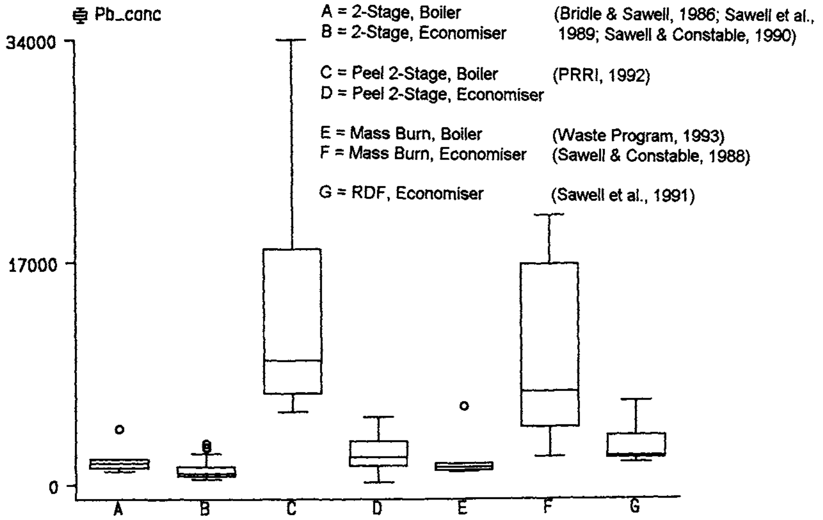


Figure 9.45 Cadmium Concentration in Bottom Ash and Grate Siftings as a Function of Combustor Type



Elements which melt easily and are capable of dripping through the grate bars into the siftings hoppers show a different behaviour. Lead data for bottom ashes and siftings and riddlings are shown in Figure 9.46. High values are found in the siftings. Generally, lead values in bottom ashes from two-stage, mass burn and RDF facilities are similar.

Figure 9.46 Lead Concentration in Bottom Ashes and Grate Siftings as a Function of Combustor Type



Results from the WASTE program study suggest that some cause and effect relationships can be observed between waste feed composition and bottom ash elemental composition. The addition of lead acid batteries increases lead concentrations in grate siftings rather than bottom ash. The lead tends to melt and become siftings and riddlings. The addition of cadmium benzoate solutions does not influence cadmium concentrations in bottom ash, rather the cadmium partitions to the fabric filter residue stream. Similar observations were made with cadmium pigment additions.

9.3.13 Influence of Aging on Bottom Ash Inorganic Characteristics

Data presented by Vehlow (1992) examine the role of aging in the composition of lead, cadmium, cooper and zinc in bottom ashes from three German facilities. No significant changes in the concentration of these elements were seen after nine months of aging.

9.4 ORGANIC CHARACTERISTICS OF BOTTOM ASH

9.4.1 Organics Present in Bottom Ash

The organic carbon content of bottom ash tends to range from 2 to 4% in well burned-out bottom ashes. The majority of this carbon is not characterised at this point in time. Examination of bottom ash samples with scanning electron microscopy suggests that much of this carbon is unburned municipal solid waste. It is possible that this carbon is cellulose, plant fibre or plastic in nature.

Trace organics of potential human health concern have been quantified in bottom ash. These include the polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzo-p-furans (PCDFs) as well as potential precursors for these compounds under certain reaction conditions. The potential precursors are chlorinated benzenes (CBs), chlorinated phenols (CPs) and polychlorinated biphenyls (PCBs). Another group of toxic compounds that may attract regulatory attention in the future are condensed polyaromatic hydrocarbons (PAHs). At present, there are 16 compounds that fall under this category; some are carcinogenic. These also have been characterised in bottom ashes. Chapter 8 discusses their presence in combustion residuals and their fate during combustion.

Compared to the many detailed data sets on physical properties or inorganic characteristics of bottom ash, the information on trace organics is very limited. Careful review of the data that are available indicate that many studies have a paucity of information about combustor operation, sampling technique and analytical methodologies. Therefore, selected data sets are presented. For the most part, the combustors listed in Table 9.1 were the basis for these data.

9.4.2 Dioxins and Furans

Table 9.20 summarises compiled data on total PCDD and PCDF concentrations found in bottom ash. Also included are total toxic equivalents according to the NATO-CCMS toxic equivalency method. The data show relatively low concentrations of PCDDs and PCDFs. Most of the isomers accounting for the typical PCDD values of 0.03 to 0.04 ng/g come from the hepta and octa groups. Most of the isomers accounting for the typical PCDF values of 0.05 to 0.1 ng/g come from the tetra and penta groups. These values are all associated with well operated mass burn facilities. Data from the RDF mass burn facility in the United States had slightly higher levels of both PCDDs and PCDFs.

Other data on PCDD and PCDF levels in bottom ash have been reported by Hiraoka et al. (1991), Klein and Tscheschlok (1989), Morselli et al. (1989) and Roffman (1991). These levels are similar to or higher than the values reported in Table 9.20. It is difficult to determine if combustor operation influenced the observed levels. The addition of boiler ash to the bottom ash process stream may have occurred.

Table 9.20

Trace Organic Concentrations (ng/g) in Bottom Ash

Country	Facility	Total Dioxins (PCDD)	Total Furans (PCDF)	1/TEQ	Total Chlorophenols (CP)	Total Chlorobenzenes (CB)	Total Polyaromatic Hydrocarbons (PAH)	Total Polychlorinated Biphenyls (PCB)	Reference
Canada	GVRD	ND[a]	ND	-	9.0	ND	181	ND	Sawell et al., 1990a
	PEI	ND	ND	-	ND	20	1,800	ND	
	LVH	ND	ND	-	34.1	6.7	2,190	ND	Sawell et al., I989b
	SWARU	0.4	<0.2	-	164	4.0	19,000	8	Sawell et al., 1989a
	QUC	ND	ND	-	14-48	6.0-13.5	125-968	ND	Sawell & Constable, 1988
Germany	A	0.036-0.039	0.096-0.102	0.0018	-	-	-	-	
	B	0.041-0.048	0.091-0.094	0.0020	-	-	-	-	
	C	0.025-0.029	0.054-0.068	0.0008	-	-	-	-	
United States	Mid-Conn	0.04-0.31	0.10-0.50	-	4-5	ND	13-29	ND	Sawell et al., 1992
	Dry Scrubber 1	-	-	-	73	18	-	-	LIRPB, 1992b
	Dry Scrubber 2	-	-	-	120	ND	-	-	
	Dry Scrubber 2	-	-	-	36	ND	-	-	
	Dry Scrubber 3	-	-	-	83	36	-	-	

[a] ND indicates not detected.

Most modern facilities are able to achieve total PCDD and PCDF levels below 0.5 ng/g. This represents a total toxic equivalent (1/TEQ) of about 10 ng/g. These levels are of the same magnitude as those seen in forty German soil samples (Hagenmaier, 1989).

9.4.3 Chlorinated Benzenes and Chlorinated Phenols

Table 9.20 also summarises compiled data on total CB and CP concentrations found in bottom ash. Typical levels are between 9 and 164 ng/g for CP and 4 and 36 for CB. These levels are considered low.

9.4.4 Polyaromatic Hydrocarbons and Polychlorinated Biphenyls

Table 9.20 also summarises PAH and PCB concentrations found in bottom ash. Typical concentrations for total PAHs range from 13 to 2,190 ng/g. Typical concentrations for total PCBs range from below detection to 8 ng/g.

PAHs are a measure of the quality of the combustion process. Significantly higher concentrations are seen in two stage systems and poorly operated mass burn facilities. Well operated incinerators can easily produce bottom ashes with total PAH concentration less than 100 ng/g. These are typical for soils in rural areas (Menzie et al., 1992).

For PCBs, regardless of which technology is employed, levels of less than 10 ng/g can be achieved. This is considered to be a low level. Higher values reported in the literature (Morselli et al., 1989; Magagni et al., 1990; Roffman, 1991, Morselli et al., 1992) may be caused by the inclusion of boiler ash in the bottom ash process stream.

9.5 CHARACTERISTICS OF GRATE SIFTINGS

Grate siftings comprise a small mass fracture of the combustion residuals produced in incineration facilities (see Chapter 8). They are usually collected in hoppers beneath the grate and added to the grate ash to produce the bottom ash process stream.

Very little information is available on the physical or chemical characteristics of grate siftings. Size ranges can vary given the spacing between grate bars on the hearth. Molten aluminum, zinc, copper and lead can drip down into the hoppers and reagglomerate as small stalagmites on the hopper walls. Visual classification shows that molten metals, fine glass and fines comprise the bulk of this material. No published information exists on the physical properties of this residue.

Data are available on the inorganic characteristics of this process stream. Recent efforts under the WASTE Program (1993) have resulted in detailed characterisation of the material. Elemental abundances from a single composite sample are shown in Table 9.21. Some of these elements were quantified over a one- week period. The range of data is shown in Table 9.22. Similar efforts were also made for an RDF facility (Table 9.23).

The bulk of the data shows that grate siftings are enriched in Al, Cu, Pb and Zn. High levels of Si are also found. Mass balances on grate siftings, grate ash and bottom ash suggest that grate siftings account for up to 40% of the total Pb loading in bottom ash. These metals can be problematic with respect to H_2 evolution during bottom ash aging, and the removal of this process stream from the bottom ash process stream warrants further consideration. It should be noted that the practice is already in use at some European facilities.

9.6 CHARACTERISTICS OF COMBINED ASH AND SCRUBBER RESIDUE

Although the various residue streams are generally separated in most countries, combined bottom ash and APC residue is presently the most prevalent waste stream from U.S. incineration facilities. There are a number of U.S. studies on the physical and chemical characteristics of combined ash. The two most recent reports (Kosson et al., 1993; LIRPB, 1993) provide a detailed description of sampling, testing and analytical procedures, as well as the data evaluation techniques used. The LIRPB (1993) study cited data on combined ash and bottom ash from 5 different facilities, whereas the study conducted for the U.S. EPA (Kosson et al., 1993) evaluated separate streams of bottom ash, APC residues and combined ash from one U.S. facility. These studies indicated that many of the physical properties of combined ash are similar to bottom ash, whereas many of the chemical properties of combined ash can be determined through proportioning the contributions from bottom ash and APC residues.

Other studies and reviews were conducted by the U.S. EPA on combined ash from a number of U.S. facilities and the reader is referred to those studies for further information on combined ash streams (U.S. EPA, 1987 & 1990).

Table 9.21
Elements Detected in Mass Burn Grate Siftings

Element	Concentration (mg/kg)	Element	Concentration (mg/kg)
Ag	64.8	Mn	1,500
Al	57,300	Mo	48
As	59.7	Na	38,000
Au	0.2	Nd	13.4
Ba	740	Ni	691
Br	0.0	Pb	9,680
Ca	68,200	Rb	25.6
Cd	22.2	Sb	305
Ce	28.6	Sc	6.2
Cl	2,110	Se	0.0
Co	24.1	Si	243,700
Cr	1,304	Sn	1.5
Cs	0.6	Sr	0.0
Cu	3,041	Ta	0.7
Dy	0.0	Tb	0.7
Eu	0.4	Th	2.4
Fe	82,300	Ti	7,000
Hf	5	U	2.0
Hg	0.0	V	79.2
In	330	W	8.3
I	0.0	Yb	0.5
K	7,900	Zn	2,140
La	13.0	Zr	266

Table 9.22
Range of Concentration of Elements in Mass Burn Grate Siftings

Element	Concentration Range (mg/kg)
Al	38,000-63,000
As	2-65
B	98-232
Ba	1349-2629
Be	<3.0
Cd	<5.0-14.6
Cr	278-562
Cu	2,347-25,215
Hg	<0.02-5.39
Ni	169-468
Pb	56,000-34,000
Sb	130-570
Se	<0.25-8.6
Sn	171-946
Zn	2,450-5334

Table 9.23
Range of Concentration of Elements in RDF Grate Siftings

Element	Concentration Range (mg/kg)
Ag	<0.9
Al	36,230-62,300
As	8-13
Ba	150-990
Be	<0.9
Bi	500-1170
Ca	51,790-92,190
Cd	5.3-12.9
Co	28-170
Cr	230-460
Cu	740-11,530
Fe	25,150-36,510
Hg	0.2-2.35
In	<0.9
Mg	7,860-12,780
Mn	490-1,170
Mo	40-120
Na	31,800-41,600
Ni	210-1,140
P	70-1,560
Pb	2,140-20,390
Sb	6-59
Se	0.3-1.8
Si	49,070-99,380
Sn	450-2,000
Te	<2.3
Ti	4,390-8,990
V	60-170
Zn	1,150-6,730

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