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# Testing of residues from incineration of municipal solid waste

Science Report P1-494/SR2



**ENVIRONMENT  
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# Executive Summary

The Environment Agency for England and Wales (EA) started a project in 2001 to consider the potential impact of the Council Directive on the Landfill of Waste 1999/31/EEC (LFD) on the quality of leachate produced in future UK landfills. As part of this project a review of leachate quality from European ash landfills was carried out (Environment Agency, 2004a). A scoping study was also commissioned to examine the significance of trace organic compounds in incinerator residues and the impact of treatment methods - carbonation and acid neutralisation - on the leaching characteristics.

A significant amount of research has been carried out on the characteristics and treatment of incinerator residues, the effect of weathering on leaching performance, and the treatment of incinerator residues. A number of researchers are interested in accelerated weathering to predict the long-term leaching behaviour of incinerator bottom ash and APC residues in landfill scenarios.

Samples of both bottom ash and fly ash/APC residues were taken from three UK incinerators and subjected to batch and column leach tests and analysis of major and trace components. It was found that the major ion and heavy metal concentrations from samples tested in this scoping study are reasonably representative of bottom ash and APC solid residues and LS 10 leach test compositions previously published in the UK and mainland Europe.

Trace organics show greater diversity and significantly higher concentrations in bottom ash than APC residues. In addition, the solvent-extracted organics from the solid residues are dominated by chlorinated aliphatics and aromatics, including trichloroethene, trichloroethane, tetrachloroethane and chlorobenzenes. The corresponding eluates are dominated by aromatic carboxylic acids, ketones, aldehydes, alcohols and esters.

Dioxins and furans, although present in significant quantities in the APC solid residues, are not detected in the eluates, even from the 9-11 day column tests.

Two treatment methods, accelerated carbonation and acid neutralisation, were carried out to assess their impact on eluate chemistry. This report concludes that the hazardous properties of incinerator residues can be reduced by carbonation due to consumption of lime and precipitation of calcite. This results in a pH reduction, although not by as much as expected under the conditions of the scoping study. However, other researchers have achieved consistent results below pH 9.

Heavy metal concentrations in eluates can also be significantly reduced, in particular Pb and Zn, Ba (bottom ash), Cu and Se (both APC). However, further work is required to evaluate the effect of carbonation on leaching Cd from APC residues. Notwithstanding this, carbonation shows promise as a treatment technology as pH reduction is achieved without significant loss of acid neutralisation capacity.

Acid neutralisation yielded far more variable replicate data than both the untreated and carbonated eluates. Heavy metal concentrations were also significantly reduced, particularly Pb and Zn. However, some metals were released in significant concentrations, in particular Cd, Sb and Mo. Cu concentrations in bottom ash eluates were also elevated, possibly due to complexation with DOC released from bottom ash samples.

Preliminary source term data are presented for both bottom ash and APC residues. Their derivation has necessarily involved a degree of subjective judgement, and they are recommended for use not as default source term values but to inform professional judgement on the selection of source term data for landfills likely to accept significant proportions of bottom ash or APC residues.

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# 1 Introduction

## 1.1 Introduction

The European Council Directive on the Landfill of Waste 1999/31/EEC (LFD), requires member states to draw up strategies to ensure the amount of biodegradable municipal waste deposited at landfill progressively reduces over a 15 year period to only 35% of the total amount produced in 1995. The LFD also requires member states to landfill only wastes that have been subject to treatment leading to a reduction in their quantity or hazard to human health or the environment.

The LFD requires three classes of landfill for:

- Hazardous waste;
- Non-hazardous waste (including municipal solid waste); and
- Inert waste.

This contrasts with the current UK practice of co-disposal of untreated biodegradable and inorganic, hazardous and non-hazardous wastes. It is anticipated that the current understanding of landfill leachate quality from UK landfills (e.g. Robinson, 1995), used to define generic source term data in the Agency's risk assessment model LandSim will not apply to some of the new classes of landfill.

This report follows on from a study of leachate quality from landfills in Europe known to contain treated MSW (by mechanical and biological pre-treatment and incineration), mixed hazardous wastes and low organic content non-hazardous wastes (Environment Agency, 2004a), that as close as possible fulfilled the following criteria:

- The site should contain only wastes that meet national criteria similar to anticipated Landfill Directive acceptance criteria;
- The site should have been engineered to modern containment standards, including a leachate collection system;
- There should exist a good length of time series leachate monitoring data, reflecting consistent waste inputs and consistent pre-treatment processes;
- Monitoring should include comprehensive coverage of leachate parameters, ideally to encompass List I organics and metals;
- There should have been a good record of compliance with the operating permit, particularly concerning waste inputs; and
- Information should be available on leachate generation rates and on gas quality and generation rates.

## 1.2 Objectives of this report

Incinerator residues were identified as a significant current and future waste stream in the UK that presented significant challenges, and uncertainties, to their management by landfilling. Such challenges included the need and options for treatment, compliance with waste acceptance criteria, long-term leachate quality and implications for the design and management of ash landfills.

The objectives of this study were to:

- Obtain representative samples of bottom ash and mixed fly ash/air pollution control residues from UK incinerators that meet current emissions standards;
- Carry out leaching tests and chemical analysis to compare the characteristics of the samples with those reported from previous studies on UK and European incinerator residues;
- Identify the concentration and composition of trace organic compounds present in solid residues and eluates to supplement data from previous studies;
- Carry out the above tests on samples artificially weathered by accelerated carbonation to assess the impact on contaminant concentrations and predict the impact of such treatment on leachate quality;
- Carry out the above tests on samples treated by acid neutralisation to assess the impact on contaminant concentrations and predict the impact of such treatment on leachate quality; and
- Prepare sets of generic source term distributions for untreated, carbonated and acid neutralised incinerator residues, in combination with data from previous studies where relevant, suitable for use in groundwater risk assessments.

## 1.3 Background information

### 1.3.1 Implications of the LFD for the landfilling of incinerator residues

Article 6a of the LFD requires waste to be treated before landfilling unless such treatment does not contribute to the objectives of the LFD or where treatment of (inert) waste is not technically feasible. Article 2 defines treatment as:

*The physical, thermal, chemical or biological processes, including sorting, that change the characteristics of the waste in order to reduce its volume or hazardous nature, facilitate its handling or enhance recovery.*

Incineration is a thermal process commonly used for the treatment of municipal solid waste (MSW), and the treatment residues would not need any further treatment to satisfy Article 6a. However, further treatment may be necessary or desirable if the treatment residues are prohibited from landfill (e.g. corrosive), do not satisfy waste acceptance criteria for a particular class of landfill, or where further treatment may enhance recovery.

#### **Classification of incinerator residues**

Residues from the incineration of MSW appear in the revised European Waste Catalogue as either absolute or mirror entries under 19 01 (European Commission, 2002). Absolute entries (solid waste from gas treatment and spent activated carbon from flue-gas treatment) are both hazardous wastes, but the evaluation of bottom ash and fly ash will depend on the presence, above threshold values, of dangerous substances against hazards H1 to H14 inclusive. Environment Agency (2003) suggests that potential hazards from metals such as Ni, Cu, Zn, As, Cd, Sb, Te, Hg, Th and Pb are considered against hazards H5-7, 10-11 and 14.

The alkaline treatment residues may be evaluated as hazardous by H4 (irritant, by risk phrase R41) or H8 (corrosive) where the pH of the leachate from leach tests is 11.5 or greater. An alkali reserve test can also be carried out that, when combined with pH, provides a measure of corrosivity (Young *et al.*, 1988). The pH can only be used to evaluate a waste against H8



where the waste is a complex mixture of substances whose composition is not determined (Environment Agency, 2003).

Corrosive wastes are banned from landfill and it would seem prudent to characterise the waste to determine whether it contains any substances within the relevant risk phrases (R34& R35). The risk phrase for lime (both CaO and CaOH) is R41 - risk of severe damage to the eyes - and the threshold concentration associated with this phrase is 10%. Such waste may therefore still be hazardous if the threshold concentration is exceeded, but as H4 (an irritant) and not H8 (corrosive). Incineration residues are therefore likely to be hazardous by H4, where the high pH can be attributed to the lime content.

### **Waste Acceptance Criteria for hazardous and non-hazardous landfills**

The treatment residues may not be disposed of at a landfill site where the waste acceptance criteria, based on standard batch leach test (British Standards Institution, 2002) or column test (Comité Européen Normalisation, 2002) results, are exceeded for a particular class of landfill. The waste acceptance criteria for granular waste come into force in July 2005 and have been set for:

- Inert landfill;
- Non-hazardous waste landfilled together with stable, non-reactive hazardous waste in non-hazardous waste sites;
- Stable non-reactive hazardous waste acceptable for disposal in certain cells at landfills for non-hazardous waste; and
- Hazardous waste landfills (European Commission, 2003).

Further treatment of incinerator residues, particularly fly ash/air pollution control (collectively referred to as APC in this report) residues, may therefore be necessary to meet waste acceptance criteria for a number of metals and anions.

## **1.4 Incinerator residues - summary of results from the Phase 1 study**

Phase 1 of the project gathered data on leachate quality from bottom ash and APC residues from research studies and commercial landfills in Europe (Environment Agency, 2004a). The key findings are summarised below.

### **1.4.1 Bottom ash**

Significant research into the quality of leachate from bottom ash has been carried out at a range of laboratory (e.g. Hjelmar, 1996) and pilot scales (e.g. Stegemann *et al.*, 1995) and full-scale landfill sites (e.g. Johnson *et al.*, 1998, 1999). The long-term monitoring of leachate quality from a mixed bottom ash (85%) and fly ash (15%) landfill cell has also been compiled by Hjelmar (pers. comm.) and partly reproduced as time-series graphs in Environment Agency (2004a).

The quality of leachate from bottom ash can be variable, but a number of key conclusions from the Phase 1 study include:

- Leachates have total dissolved solids similar to, or slightly higher than, typical UK MSW landfills, with dominant ions each typically in the range 1,000 to 10,000 mg/l;
- The dominance of major anions and cations is: Cl > SO<sub>4</sub> and Na > K > Ca > Mg;
- pH values are usually elevated, typically in the range 8.5 to 11.5;
- pH values and the leaching of some heavy metals are strongly affected by carbonation, and elevated concentrations (1 to 10 mg/l) of some metals, mainly Mo, W, Cu, Pb and Zn, may occur;

- TOC concentrations may be similar to dilute methanogenic MSW leachate but are of unknown composition.
- Ammoniacal nitrogen concentrations are typically much lower than in dilute methanogenic MSW leachate.

### 1.4.2 APC residues

Data were collected from a range of laboratory and field scale studies on the chemistry of APC residues. Hjelmar (1996) reported the typical contaminant concentrations from low LS ratio leach tests on APC residues derived from wet, dry and semi-dry scrubbing processes. These data were combined with leachate monitoring results from three landfills, two mono-fill sites with the ash delivered and deposited in “big bags” and one landfill with cells receiving separate ash from semi-dry and wet processes.

Chemical rather than biological processes dominate fly ash/APC residue leachate chemistry. In an ash landfill carbonation along preferential flow paths is thought to have a significant role in modifying leachate chemistry. Key conclusions from the study include:

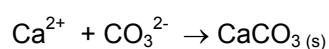
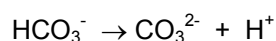
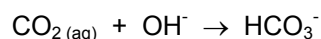
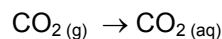
- High concentrations of dissolved solids, typically 50,000 to 150,000 mg/l, dominated by Na and Cl;
- TOC and NH<sub>4</sub>-N concentrations may range from several mg/l to 10s of mg/l;
- Concentrations of heavy metals may be high, especially Pb (up to > 1,000 mg/l from dry and semi-dry processes) and Cd (tens to hundreds of µg/l, occasionally mg/l levels);
- Dry/semi-dry APC scrubbing can result in several orders of magnitude difference in the leachate concentration of major ions and metals than wet-scrubbing processes; many components show extreme fluctuations from one sample to the next;
- Leachate pH is typically near neutral but occasional spikes to pH ~11, showing the persistence of high pH conditions within the waste matrix; and
- Wet scrubbing processes give rise to near-neutral pH leachate, without the high pH spikes evident in landfill leachate from dry and semi-dry processes.

No information was obtained for a number parameters of interest, particularly trace organics.

## 1.5 The impact of carbonation on leachate quality

Carbonation is a natural phenomenon that occurs when highly alkaline fluids are exposed to atmospheric carbon dioxide, resulting in a reduction in pH and precipitation of calcite (Khoury *et al.*, 1985). Carbonation proceeds along the following reaction sequence (after Clark *et al.*, 1992):

#### Carbonation reactions



Carbonation will ultimately lead to a reduction in pH, to around pH8.3 for a calcite-buffered system. This is usually a slow process, although in the high temperatures in the Middle East carbonation depths of several mm may occur in as many days (Walker, 2002).

In a northern European ash landfill scenario, the matrix/pore water will likely maintain alkaline pH for many thousands of years (Astrup *et al.*, 2001). Astrup *et al* (*op cit.*) also suggest that carbonation will lead to an initial drop in pH due to conversion of hydroxides to carbonates, but that alkalinity will not be removed from the system as a result.

Carbonation can be accelerated by exposing alkaline materials to a carbon dioxide-enriched atmosphere. Researchers claim that accelerated carbonation has significant advantages over conventional hydration (water) based solidification/stabilisation technologies (Lange *et al.*, 1996, 1997, Sweeney *et al.*, 1998), namely:

- Reduced leachability of some metal cations as the pH is lower in a fully carbonated system (to around 8.3);
- Conversion of metal cations to metal carbonates (rather than hydroxides) and/or possibly metal-silanol complexes (M - O - Si);
- Greater stability of the solidified/stabilised material and reduced permeability through the precipitation of calcite in pore spaces; and
- Absorbs the greenhouse gas, carbon dioxide (the mass of carbon dioxide bound is typically 25-50% of the mass of the binder).

# 2 Experimental programme

## 2.1 Overview

At the time of this study there were twelve operational incinerators for MSW in the UK. Their ages and throughput vary considerably. Three for this study were nominated by the EA, to provide a reasonable coverage of different ages, sizes, population catchments and equipment designs.

All three plants were visited in order to assess the logistics of sampling and to provide the operators with more detailed information about the project prior to their giving approval for sampling to go ahead.

An assurance was given to the operators that the incinerators would not be identified in the published results. It is therefore not possible to give full details of the individual plants. The following summary information can be provided:

- All three meet the current air emissions standards;
- The combined tonnage burnt at the three plants is approximately 1Mt/a;
- At all three plants a minor proportion of the material burnt consists of non-hazardous industrial waste together with very small tonnages of certain clinical wastes. The remainder, comprising a high percentage of total inputs, is MSW;
- All three plants used semi-dry scrubbing with lime, for the removal of acid gases, in common with all other UK incinerators for MSW; and
- All three plants use powered activated carbon, injected into the lime scrubber, for the removal of dioxins.

The experimental programme is shown schematically in Figure 1 and is described in detail in later sub-sections.

The approximate dates of the various stages were as follows:

1. Sampling from the incinerators	27 May 2002 to 24 June 2002
2. Carbonation	late May 2002 to late June 2002
3. Stage 1: analysis of solids	May 2002 onwards
4. Stage 2a: aqueous leaching tests at LS 10	Mid-June to mid-July 2002
5. Stage 2b: acid-neutralised leaching tests at LS 10	mid-Sept. to mid-October 2002
6. Stage 3: column leaching tests	late October to mid-Nov. 2002

All analytical results were received by mid-February 2003.

## 2.2 Sampling programme and sampling methodology

Details of the sampling and quantities sampled at each plant are shown in sampling logs in Appendix A. An overview of the sampling and testing approach is given in Figure 1.

### 2.2.1 Bottom ash (BA)

The sampling protocol given below was used, to provide approximately 100 kg of homogeneous working stock, stored in polyethylene bins with snap-top lids.

The plant operator provided several sub-samples, of typically 0.2 to 0.5 tonnes each, taken from different parts of the main bottom ash stockpile. This was typically done using the bucket of a Bob-cat, JCB or similar.

The bucketfuls were combined on an area of concrete hard standing at the site. The machine bucket was then used to carry out an initial mixing of the sub-samples.

Project staff then took random shovelfuls from the mixed pile, of typically 2–4 kg each, and placed them onto a steel sieve with a 12 mm mesh size. The hand shovel was stainless steel. The sieve measured approximately 1 m x 2 m and was supported at each corner approximately 0.5 m above a new polyethylene sheet laid on the ground.

While one member of the project team shovelled, the other used two mild steel hand trowels to move the ash back and forth across the sieve, to encourage materials to fall through. Unusually large items (>~100 mm) were removed by hand from the sieve and placed in a separate reject pile.

Periodically, the sieve was emptied of all oversized materials, to allow efficient sieving of further ash. Prior to removing the oversized materials, the sieve was banged up and down sharply several times to encourage more fine materials to pass through.

All oversized materials collected from the sieve were retained with the larger items, for weighing.

When enough material had been sieved, the sieved fraction on the polythene sheet was homogenised by the method of coning.

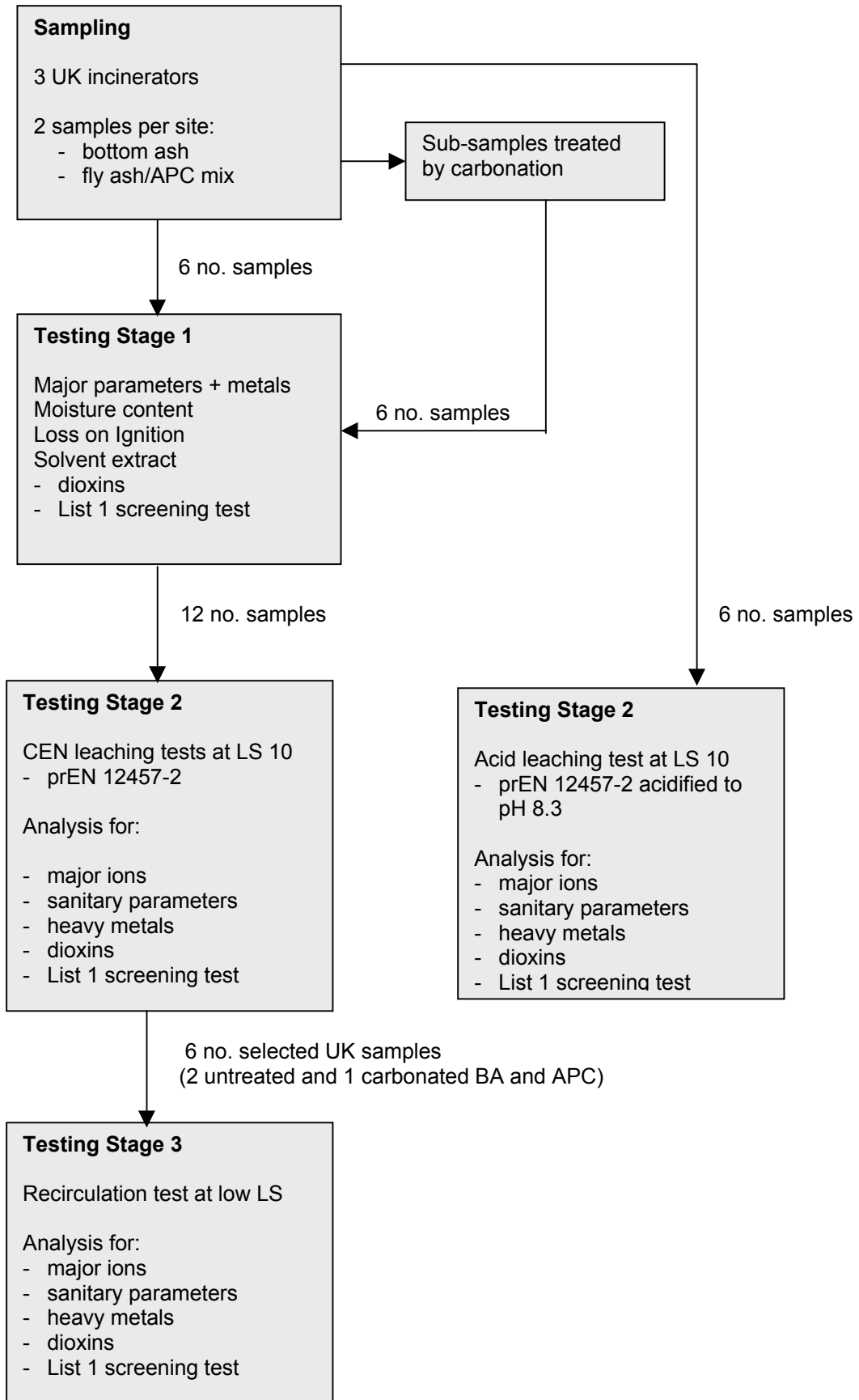
The homogenised material was then placed by hand shovel into five numbered polyethylene bins. Some further homogenisation was achieved during this process by placing consecutive shovelfuls in each of the bins in turn.

The oversized sieve rejects were also shovelled into bins.

All bins were then weighed. The recorded weights are shown in the sampling logs in Appendix A.

The proportions of rejects (i.e. >12 mm) were:

Site 1	36 % w/w
Site 2	33 % w/w
Site 3	44 % w/w



**Figure 1. Schematic summary of MSWI residue sampling and testing**



**Plate 1 Sieving bottom ash**



**Plate 2 Sieved bottom ash**



**Plate 3 Bottom ash after coning**



**Plate 4 Rejects from sieving**

## 2.2.2 Fly ash and air pollution control residues (APC)

It was decided that the study would focus on combined fly ash and air pollution control residues, rather than either of them separately. At the large majority of plants in the UK, the two materials are collected in admixture, via baghouse filters downstream of the scrubbing towers, and where they are collected separately, they are nevertheless normally disposed of together. At most UK plants there would be practical difficulties in obtaining samples of either material separately. It was decided that the budget available for leaching tests and chemical analysis was best allocated to combined samples, without any significant loss of useful information.

The sampling procedures given below were developed site by site, to provide approximately 30kg of homogeneous working stock of combined residue (APC) from each plant stored in polyethylene bins with air-tight snap-on lids.

At Site 1, the operator collected APC material, over a 48 hour period immediately before our visit. Small sub-samples were taken at regular intervals and stored in six plastic bins, three for each of the two incinerator production lines. During the visit, all six sets of material were then mixed and homogenised on site, using the method of coning, on a polythene sheet, as described above for bottom ash. The homogenised material was then transferred on site into four bins, to a volume of ~20 litres each. Materials were added from the mixed stockpile into the four bins sequentially so that a further degree of mixing and homogenisation took place.

At Site 2, APC material was collected during our sampling visit, directly from two silos, each filling one plastic bin. The bins' contents were then mixed and homogenised subsequently at the Enviro laboratory, using the method of coning on a polythene sheet.

At Site 3, the operator collected APC material on our behalf, over 48 hours prior to our visit. Samples were taken at hourly intervals from a single sampling point. These were combined into two polythene bags, one for each 24 hour period prior to our visit. The bag contents were

subsequently combined and homogenised at the Enviroc laboratory and then stored in plastic bins, fitted with snap-top lids.

All bins were weighed after filling. The recorded weights are shown in the sampling logs in Appendix A.

Photographs of the mixed APC material are shown below.



**Plate 5 APC residue during coning**



**Plate 6 APC after coning**

## 2.3 Carbonation

One bin of bottom ash and one of APC residue from each site were sent for carbonation at a pilot facility operated by Lafarge Envirocem Systems, at Barnstone, Nottinghamshire. A short report by Lafarge, describing the equipment, procedure and some details of the materials treated, is shown at Appendix B. Photographs of the equipment are shown in Plates 7 and 8.



**Plate 7 Carbonation pilot plant**



**Plate 8 Carbonation pilot plant**

## 2.4 Leaching tests at LS 10

Leaching at LS 10 was used for most of the testing because the test is easy and quick to undertake, and there is a large body of published data on LS 10 tests.



## 2.4.1 Aqueous leaching tests

Aqueous leaching tests were carried out on each material, using the European standard single step procedure, prEN 12457-4 (now published as BS EN 12457-4, BSI 2002), with the following variations or departures (the relevant section of prEN-12457-4 is referenced in italics).

The bottles were glass with polypropylene caps. *[section 4.2.1]*

The roller table rotated at 6 rpm rather than 10 rpm. *[section 4.2.2]* Visual observation confirmed that good mixing was achieved.

A GF/D fibreglass filter was used beneath the 0.45  $\mu\text{m}$  membrane filter. This technique speeds up filtration rates without affecting filtration efficiency. *[section 4.2.4]*

De-ionised water. *[section 4.2.15]*

For Site 1 APC residue the agitation period was only 22 hours rather than 24. *[section 5.2.1]*

Conductivity, temperature and pH of the eluates were not measured in situ. *[section 5.2.2]*

The sieve size was 12 mm, rather than 10 mm

The procedure stipulates the method outlined below for ensuring a LS ratio of 10:1 on a dry weight basis, with exactly 90 g of dry mass.

From the measured moisture content  $[\text{H}_2\text{O}]$ , the following values are calculated:

- $[\text{H}_2\text{O}]$  - the ratio of moisture:whole mass (%)
- DR - the ratio of dry mass:whole mass (%)
- MC - the moisture content ratio,  $[\text{H}_2\text{O}]/\text{DR}$
- Mw - the mass of undried solid to be used in the test is given by:  $90 \text{ g} \times 100/\text{DR}$
- L - the volume of leachant added, is given by:  $90 [10 - \text{MC}] \text{ ml}$

Table 1 shows the calculation of the quantities used for each material. Five replicate tests were done for each material. Appendix C shows the testing log, with details of all replicates.

The requisite amount of solid material was taken from one bin (selected at random, in cases where several bins of a given source existed). Material was taken by spatula from several locations. In the case of the bottom ashes, a certain degree of weak cementation had taken place during storage. The material in the chosen bin was broken up and re-mixed prior to sampling, by rolling and up-ending the bin several times.

The apparatus used in the LS 10 tests is shown in Plates 9 and 10.



Plate 9 Roller table in operation



Plate 10 LS 10 test close up

**Table 1 Quantities of MSWI residue and leachant used in aqueous leaching tests**

	units	untreated BA	carbonated BA	untreated APC residue	carbonated APC residue
<b>Site 1</b>					
[H <sub>2</sub> O]	%	19	14	0	20
DR	%	81	86	100	80
MC = [H <sub>2</sub> O]/DR		0.235	0.163	0	0.167
∴ solid used in test, M <sub>w</sub>	g	111.1	104.7	90.0	108.0
Leachant added in test, L	ml	880	885	900	900 <sup>(1)</sup>
<b>Site 2</b>					
[H <sub>2</sub> O]	%	35.4	15.9	0	9.7
DR	%	64.6	84.1	100	90.3
MC = [H <sub>2</sub> O]/DR		0.548	0.189	0	0.107
∴ solid used in test, M <sub>w</sub>	g	139.3	107.0	90.0	99.7
leachant added in test, L	ml	851	883	900	890
<b>Site 3</b>					
[H <sub>2</sub> O]	%	18.5	13.1	0	9.7
DR	%	81.5	86.9	100	90.3
MC = [H <sub>2</sub> O]/DR		0.227	0.151	0	0.107
∴ solid used in test, M <sub>w</sub>	g	110.4	103.6	90.0	99.7
leachant added in test, L	ml	880	886	900	890

Notes to table: 1 - This volume should have been 885 ml but the amount actually added was 900 ml.

## 2.4.2 Acid neutralisation leaching tests

These tests also followed prEN 12457-4, but used a mixture of deionised water and nitric acid as the leachant. The intention of these tests was to add an amount of acid, as part of the leachant, such that at the end of the agitation period the pH would be 8.3. This is the value expected if all of the free lime had been carbonated. It was anticipated that acid neutralisation might be used as a treatment method to immobilise amphoteric metals.

In practice the pH of 8.3 proved to be a difficult target to hit. Even with the benefit of an initial sighting test, the first set of leaching tests had to be discarded because the pH values were too high. A further set of sighting tests had to be undertaken before a reasonably satisfactory set of pH values could be obtained.

The results of the initial sighting tests are shown in Table 2. In this test, samples of each waste were slurried with water and titrated against molar nitric acid. The acid needed to reach a pH value of 8.3 was used to calculate acid additions to be used in the leaching tests.

Three initial sets of leaching tests were then done on the first waste, Site 1 BA, with acid additions at 75%, 100% and 125% of the amount calculated from the sighting test for a pH of 8.3. This range of additions was used to allow for additional acid/waste interactions during the 24 hour agitation period and for variations due to the heterogeneity of the waste. Five replicates were done at each level of acid addition. At the end of the agitation period the pH was checked in one bottle of each set of five. The set with a pH value nearest to 8.3 was to be selected and the remaining four bottles in that set used for chemical analysis. The other two sets were to be discarded.

**Table 2 Results of initial acid neutralisation sighting tests on MSWI residues**

Sample reference	pH at start	Acid required to pH 12	Acid required to pH 8.3	Acid required to pH 4
Site 1 BA	12.7	230	410	550
Site 2 BA	12.1	30	190	580
Site 3 BA	12.6	310	625	900
Site 1 APC	12.0	100	3060	6030
Site 2 APC	12.3	1150	5800	8180
Site 3 APC	12.7	3900	6840	9600

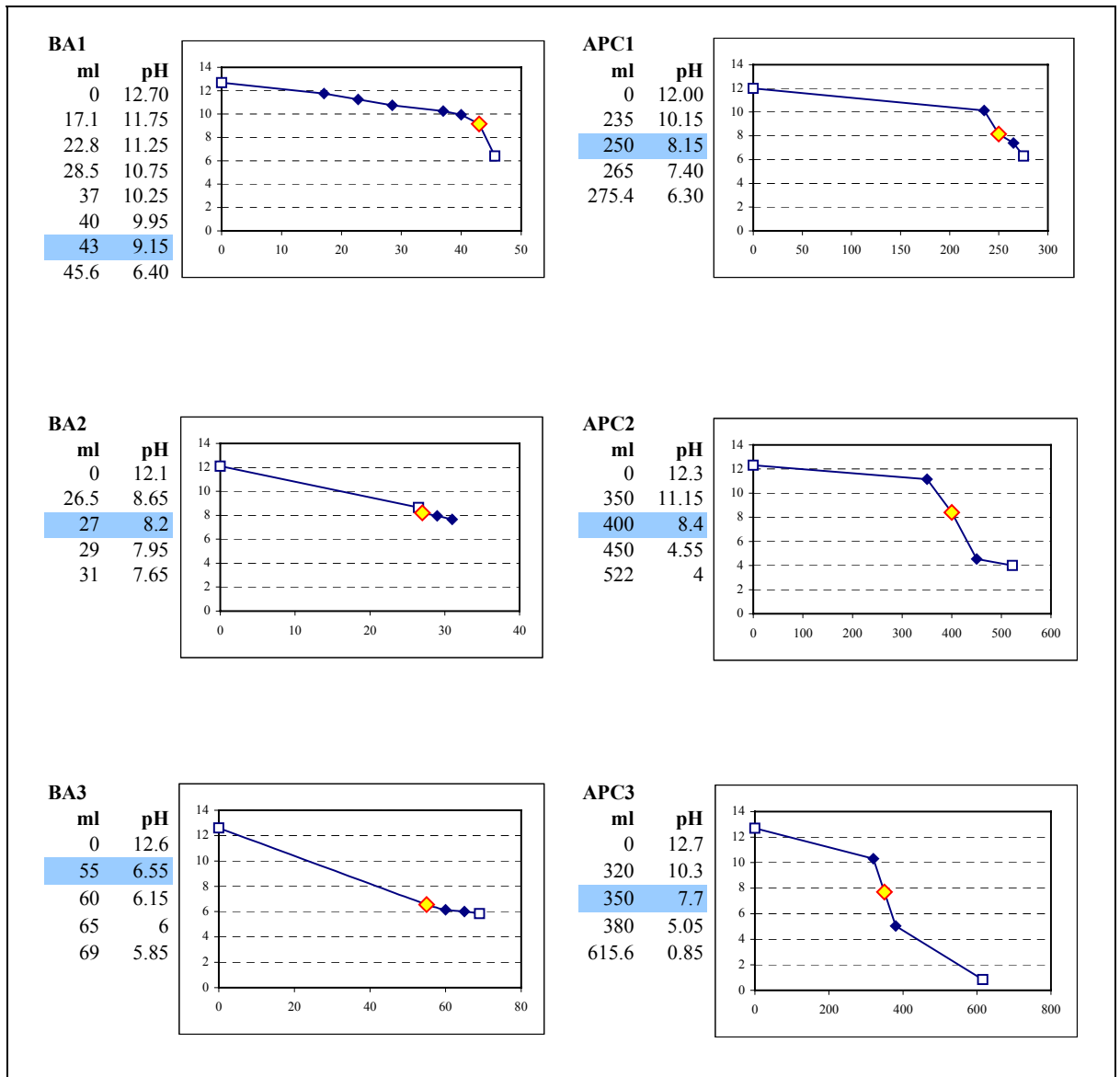
Weight recorded, water added sufficient to make mobile on magnetic stirrer, titrated vs pH meter with molar nitric acid. Figures are in millilitres of acid per kilogram (= mmole/kg).

In practice, the pH values obtained in this initial test on Site 1 BA were 11.75, 11.25 and 10.75, at the three levels of acid addition. A second set of sighting tests was therefore conducted on all six wastes. These followed the LS 10 leaching test procedure, but used double the amount of acid indicated by the first sighting tests. Based on the pH results from this second sighting test, revised estimates were made of acid additions needed to reach pH 8.3. For each waste, three sets of five replicates were undertaken, with acid additions at 75%, 100% and 125% of the new estimated requirement. As before, one bottle from each set was chosen at random for pH measurement and the set with a pH value closest to 8.3 was used for chemical analysis.

The pH values obtained in all of the sighting tests and leaching tests on each material are shown in Figure 2. Appendix D shows the testing log for the acid neutralisation leaching tests. The samples selected for chemical analysis are highlighted in Figure 2 and in Appendix D. The quantities of acid needed to reach a pH value of 8.3 have been estimated from Figure 2 and are presented in Table 3.

**Table 3 Acid neutralisation capacity of MSWI residues estimated from 24-hour leaching tests (to pH 8.3)**

	Volume of 2M HNO <sub>3</sub> to pH8.3 (ml)	Dry weight of residue (g)	ANC to pH8.3 (mol/kg)
<b>Bottom Ash</b>			
Site 1	44	90	0.98
Site 2	27	90	0.60
Site 3	53	90	1.18
<b>APC residue</b>			
Site 1	250	90	5.56
Site 2	400	90	8.89
Site 3	340	90	7.56



**Figure 2** pH results obtained during acid neutralisation leaching tests and sighting tests

[X-axis shows ml of 2M HNO<sub>3</sub> added to 90 g dry weight of residue;  
 Y-axis shows pH value obtained;  
 open square symbol shows values from the two sighting tests;  
 highlighted values are the set used for chemical analysis]

## 2.5 Column leaching tests

Column tests were carried out to examine equilibrium leachate quality at low LS ratio, which is more representative of the first few decades at a landfill. Wastes were placed in perspex columns and a fixed amount of water recirculated through the waste until a constant electrical conductivity was reached.

The budget and timescales allowed only six materials to be tested and these were as follows.

Site 1	untreated BA
Site 2	untreated BA
Site 2	carbonated BA
Site 1	untreated APC
Site 1	carbonated APC
Site 2	untreated APC

These were chosen before analytical results were returned from the LS 10 tests and were selected mainly because these wastes had exhibited pH values closest to the theoretical calcite-buffered value of 8.3, in the acid tests at LS 10. They were therefore felt likely to provide the best basis for comparison with LS 10 results from untreated waste, carbonated waste and acid-neutralised waste.

The equipment used is shown schematically in Figure 3 and the filled columns are illustrated in Plates 11–13 (these show the columns filled with bottom ash). The columns were 120 mm internal diameter x 1,000 mm high.



Plate 11 Columns filled with bottom ash

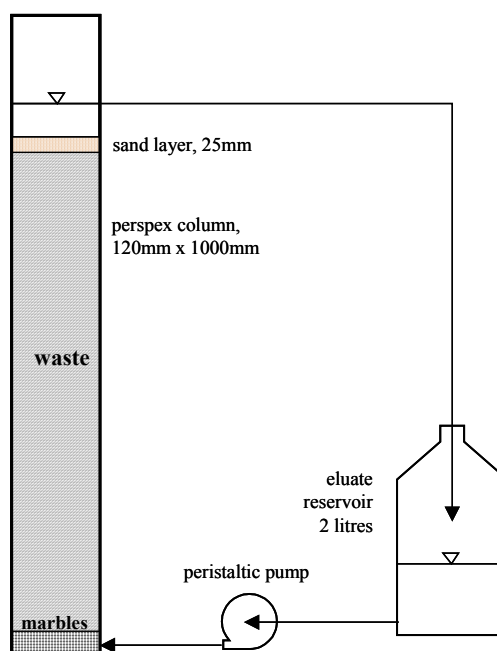
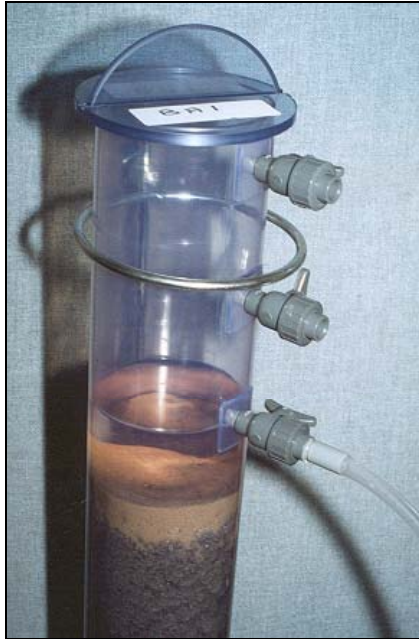
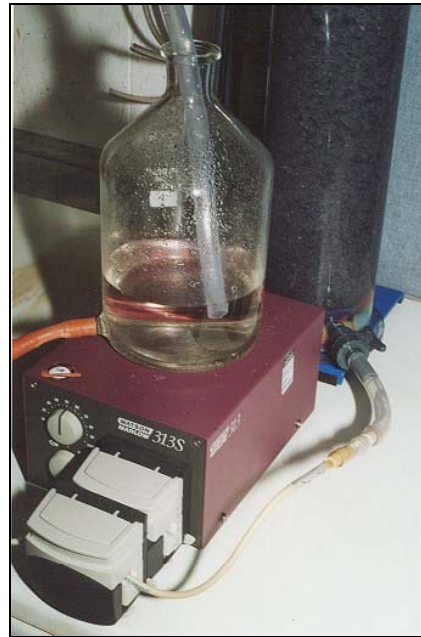


Figure 3 Schematic of the column leaching test



**Plate 12 Column test, detail**



**Plate 13 Column test, detail**

The columns were operated in an upflow saturated mode. Liquid overflowed from one of three valved outlets, to a 2 litre pyrex reservoir, and was pumped back into the base of the column by a peristaltic pump. To assist even recirculation, a layer of glass marbles was placed in the base of each column before the waste was introduced. To minimise carry over of fines from the waste, a layer of clean washed sand was placed on top of the waste. The recirculation rate was set so as to give a hydraulic retention time, per pass, of ~1 day. This was achieved by setting timers to operate the pumps for 30 minutes per hour at a rate of ~7 ml/minute. Details of the quantities and recirculation rates are shown in Table 4.

**Table 4 Details of column leaching tests on MSWI residues**

	units	BA1	BA2	tBA2	APC1	APC2	tAPC1
Mass of waste used	kg	16(E)	16(E)	16(E)	4.738	4.547	5.969
Initial volume of waste	litres	8	8	8	8	8	8
Recirculation rate	l/d	5.04	5.04	5.04	5.04	5.04	5.04
Water added	litres	4	5	5	8	8	7
Approximate LS ratio		0.5	0.5	0.5	1.7	1.7	1.7
Duration of test	hours	278	278	278	218	218	218
Total volume recirculated	litres	58	58	58	46	46	46
Initial moisture content	%w/w	19	35.4	15.9	0	0	20
∴ Bed Volume of waste	litres	3.04	5.66	2.54	0	0	1.19
No. of BV recirculated		19	10	23	-	-	39

[Bottom ash was not weighed: estimated weight is based on a bulk density of 2 kg/l]

Electrical conductivity was measured twice daily. The recirculation was continued until it was clear that a quasi-steady state had been reached. Recirculation was then stopped and the columns allowed to drain. All of the leachate was collected and samples sent to the EA laboratories for analysis. During the tests on untreated APC residue, flammable gas was evolved, thought to be mainly hydrogen. This led to some lifting of the waste mass, due to bubbles, and a small amount of liquid was lost via an open valve at a higher level than the

leachate outflow pipe. Additional water was added to make up the estimated losses: 2 litres to APC 2 and 1 litre to carbonated APC1.

The column tests were carried out in two sets, one for bottom ash and one for APC residue. A blank (empty column) was run with the APC set. Details of the daily measurement of conductivity in the two sets of trials are shown at Appendix E.

## 2.6 Chemical analysis

The Environment Agency's National Laboratory Service carried out all chemical analysis on solids and eluates. Samples were submitted as they were produced, from June to November 2002. A log of the dates of sample submission and receipt of results is shown at Appendix F.

All samples were analysed for a range of sanitary parameters, major ions, heavy metals, and dioxins. In addition a screening technique for List 1 substances (Environment Agency, 1999) was carried out on all samples (solids and eluates).

# 3 Results

## 3.1 General observations

Some general observations on the MSWI residues and the leaching tests are given below.

There was a considerable variation in the proportion of unburned material in the bottom ash at the three incinerators. Paper and card with print still legible occurred to some extent at all three sites. Visually, it was most prevalent at Site 2 and least prevalent at Site 3. However, most of this type of material was removed with the other 12 mm rejects during the sieving procedure. The results for Loss on Ignition therefore do not take account of unburnt oversized material.

The bottom ash samples underwent a degree of solidification during storage between sampling and the leaching tests. This period was 2.5–3 weeks for all three sites. The extent of cementation was slight and the materials were easily broken up again by rolling and up-ending the sealed plastic container.

Carbonation caused only minor colour changes in the materials and, visually, had little effect on their physical form. The carbonated APC residues appeared to become more dense, possibly as a result of the uptake of moisture.

Considerable gas generation occurred in the two column tests on untreated APC residue. No visible evidence of gas generation was observed from the carbonated APC residue, and none from any of the bottom ash samples. The gas was flammable and is thought to have been hydrogen. Evolution of hydrogen following hydration has been observed elsewhere in studies on APC residues (e.g. Chen *et al.*, 2003). It is assumed to be derived from the reaction of finely divided metal particles (e.g. Al) with water.

## 3.2 Results of analysis of solid residues

Analytical results for conventional inorganic parameters are shown in Table 5.

Results were not received for some parameters on certain samples. This applies mainly to SO<sub>4</sub>, Cl and total nitrogen. No results were received for Hg on any solid sample.

Results for dioxin analysis on solid samples are shown in Table 6 (bottom ash) and Table 7 (APC residue).



**Table 5 Analysis of solid MSWI residues for metals and other inorganic determinands**

Determinand	Units	Bottom ash samples						APC residues					
		untreated			carbonated			untreated			carbonated		
		BA 1	BA 2	BA 3	TBA 1	tBA 2	tBA 3	APC 1	APC 2	APC 3	tAPC 1	tAPC 2	tAPC 3
Loss on drying at 105°C	%	19.9	22.2	17.5	14.5	18	10.9	0.2	1.47	0.77	16.5	15.3	14.1
Loss on drying at 450°C	%	21.4	25.3	20.8	17	23.3	15.8	1.57	0	1.1	20.2	19	16.1
Calculated Lol	%	1.5	3.1	3.3	2.5	5.3	4.9	1.37	-1.47	0.33	3.7	3.7	2
SO <sub>4</sub> (acid soluble)	mg/kg	21000			16000			56000			51000		
SO <sub>4</sub> (leachable)	mg/kg	2000			4000			31000			11000		
Cl (total)													
Cl (leachable)	mg/kg	1200			1600			160000			130000		
HCO <sub>3</sub>													
NH <sub>4</sub> -N (leachable)	mg/kg	9.8	<1.00	<1.00	4.4	<1.00	<1.00	5.9	<1.00	<1.00	5.3	<1.00	<1.00
Total N (leachable)	mg/kg	27			16			13			9.3		
CN (total)	mg/kg	<1.0	<0.50	<0.50	<1	<0.50	<0.40	<1	<0.40	<0.50	<1	<0.50	<0.50
total metals: Na	mg/kg	4700	6100	5000	5000	6800	5600	19000	14000	15000	16000	15000	14000
K	mg/kg	3600	2400	3500	3800	3100	2900	29000	14000	26000	24000	15000	24000
Ca	mg/kg	69000	52000	57000	62000	58000	58000	260000	260000	260000	210000	280000	230000
Mg	mg/kg	3900	4300	3100	3700	5700	5300	3900	4900	6200	3400	5100	5900
Fe	mg/kg	39000	39000	68000	56000	59000	80000	3800	6200	7300	3000	5200	6700
Mn	mg/kg	480	410	520	490	480	540	270	253	400	210	240	380
Al	mg/kg	41000	22000	21000	58000	32000	24000	17000	21000	22000	13000	20000	20000
Hg	mg/kg												
Cd	mg/kg	<20	4.3	4.8	<20	4.7	5.3	130	53	86	110	49	74
Cr	mg/kg	62	110	62	140	170	160	67	69	86	54	63	75
Cu	mg/kg	3000	910	720	43000	2600	870	900	300	360	700	250	330
Pb	mg/kg	620	980	810	910	1400	510	3500	1300	1700	2800	1200	1600
Ni	mg/kg	45	65	36	95	180	110	28	19	45	22	19	34
Zn	mg/kg	2100	1300	940	4000	1800	1100	11000	3600	7000	8800	3400	6100
Sb	mg/kg	<20	<10.0	55	<20	<10.0	<20.0	260	86	170	100	67	125
Mo	mg/kg	53			80			40			31		
V	mg/kg	22			21			16			12		
Ba	mg/kg	350			430			63			190		
Tl	mg/kg	<20			<20			<20			<20		
Se	mg/kg	<20			<8			<8			<8		
Sn	mg/kg	160			<20			710			490		

**Table 6** Dioxin analysis of bottom ash from three UK MSW incinerators  
(all in ng/kg)

Analyte	Untreated			carbonated		
	BA 1	BA2	BA3	t-BA1	t-BA2	t-BA3
1,2,3,4,6,7,8-heptachlorodibenzo-p-dioxin	<50.13	<31.40	<21.78	<50.62	<b>404.9</b>	<42.47
1,2,3,4,6,7,8-heptachlorodibenzofuran	<17.29	<66.31	<28.37	<b>55.13</b>	<b>101.7</b>	<20.65
1,2,3,4,7,8,9-heptachlorodibenzofuran	<49.24	<34.46	<10.66	<21.49	<13.84	<19.76
1,2,3,4,7,8-hexachlorodibenzo-p-dioxin	<64.68	<8.536	<2.493	<3.811	<28.40	<5.690
1,2,3,4,7,8-hexachlorodibenzofuran	<23.85	<6.268	<3.588	<b>19.45</b>	<24.78	<6.884
1,2,3,6,7,8-hexachlorodibenzo-p-dioxin	<11.39	<8.323	<6.034	<b>12.87</b>	<39.22	<8.680
1,2,3,6,7,8-hexachlorodibenzofuran	<30.38	<5.873	<24.12	<14.36	<29.20	<22.25
1,2,3,7,8,9-hexachlorodibenzo-p-dioxin	<186.2	<17.84	<6.452	<b>13.79</b>	<23.72	<2.801
1,2,3,7,8,9-hexachlorodibenzofuran	<25.74	<4.480	<5.539	<14.48	<12.19	<2.662
1,2,3,7,8-pentachlorodibenzo-p-dioxin	<26.34	<9.326	<1.880	<7.224	<16.27	<5.383
1,2,3,7,8-pentachlorodibenzofuran	<16.07	<17.16	<b>6.55</b>	<5.485	<13.55	<5.552
2,3,4,6,7,8-hexachlorodibenzofuran	<25.68	<18.21	<8.642	<b>23.62</b>	<15.69	<11.20
2,3,4,7,8-pentachlorodibenzofuran	<18.68	<12.83	<4.128	<9.085	<16.97	<6.177
2,3,7,8-tetrachlorodibenzo-p-dioxin	<12.17	<3.871	<5.127	<b>3.611</b>	<5.636	<1.874
2,3,7,8-tetrachlorodibenzofuran	<11.27	<2.775	<11.13	<b>7.851</b>	<11.47	<6.778
octachlorodibenzo-p-dioxin	<182.2	<122.6	<147.5	<b>105.2</b>	<b>525.3</b>	<266.9
octachlorodibenzofuran	<30.16	<20.17	<71.89	<46.32	<63.38	<47.68
<b>Total (ng/kg)</b>	<	<	<b>6.5</b>	<b>241</b>	<b>1032</b>	<
<b>Total (ngTEQ/kg)</b>	<	<	<b>0.3</b>	<b>11.9</b>	<b>5.1</b>	<

**Table 7 Dioxin analysis of APC residue from three UK MSW incinerators**  
(all in ng/kg and in TEQ/kg)

Analyte	WHO TEQ factor	untreated						carbonated					
		APC1		APC2		APC3		t-APC1		t-APC2		t-APC3	
		ng/kg	TEQ/kg	ng/kg	TEQ/kg	ng/kg	TEQ/kg	ng/kg	TEQ/kg	ng/kg	TEQ/kg	ng/kg	TEQ/kg
1,2,3,4,6,7,8-heptachlorodibenzo-p-dioxin	0.01	4241	42.4	3847	38.47	1397	13.97	2613	26.13	4037	40.37	1463	14.63
1,2,3,4,6,7,8-heptachlorodibenzofuran	0.01	4879	48.79	2161	21.61	1304	13.04	3287	32.87	2166	21.66	1045	10.45
1,2,3,4,7,8,9-heptachlorodibenzofuran	0.01	784.9	7.849	269.3	2.693	116.4	1.164	691	6.91	370.8	3.708	94.16	0.9416
1,2,3,4,7,8-hexachlorodibenzo-p-dioxin	0.1	289.4	28.94	310.1	31.01	102.4	10.24	183.1	18.31	306.7	30.67	110.2	11.02
1,2,3,4,7,8-hexachlorodibenzofuran	0.1	1418	141.8	982.8	98.28	575.9	57.59	942.1	94.21	1012	101.2	486.1	48.61
1,2,3,6,7,8-hexachlorodibenzo-p-dioxin	0.1	563.3	56.33	604.1	60.41	271.4	27.14	318.5	31.85	738.3	73.83	225	22.5
1,2,3,6,7,8-hexachlorodibenzofuran	0.1	1242	124.2	1193	119.3	666.7	66.67	926.2	92.62	890	89	505.1	50.51
1,2,3,7,8,9-hexachlorodibenzo-p-dioxin	0.1	498.8	49.88	571.6	57.16	311.8	31.18	318.4	31.84	490	49	181.5	18.15
1,2,3,7,8,9-hexachlorodibenzofuran	0.1	<283.2	0	425.6	42.56	106.8	10.68	<396.6	0	305.6	30.56	130.2	13.02
1,2,3,7,8-pentachlorodibenzo-p-dioxin	1	323.3	323.3	474.8	474.8	245.7	245.7	238.9	238.9	382.7	382.7	168.2	168.2
1,2,3,7,8-pentachlorodibenzofuran	0.05	886.9	44.345	960.4	48.02	706	35.3	36.37	1.8185	378.8	18.94	531.9	26.595
2,3,4,6,7,8-hexachlorodibenzofuran	0.1	1816	181.6	1110	111	525	52.5	1151	115.1	925.1	92.51	432.7	43.27
2,3,4,7,8-pentachlorodibenzofuran	0.5	1245	622.5	1051	525.5	744.1	372.05	54.02	27.01	1130	565	481.7	240.85
2,3,7,8-tetrachlorodibenzo-p-dioxin	1	<72.46	0	135.5	135.5	103.6	103.6	53.96	53.96	171.6	171.6	85.58	85.58
2,3,7,8-tetrachlorodibenzofuran	0.1	413	41.3	721.4	72.14	571.4	57.14	285.8	28.58	706.5	70.65	407.7	40.77
octachlorodibenzo-p-dioxin	0.0001	8582	0.8582	4359	0.4359	2716	0.2716	7770	0.777	6234	0.6234	2449	0.2449
octachlorodibenzofuran	0.0001	247.1	0.02471	699.8	0.06998	186.9	0.01869	1669	0.1669	691.1	0.06911	219.5	0.02195
<b>Total</b>		<b>27,430</b>		<b>19,876</b>		<b>10,651</b>		<b>20,538</b>		<b>20,936</b>		<b>9,016</b>	
<b>Total TEQ</b>			<b>1714</b>		<b>1839</b>		<b>1098</b>		<b>801</b>		<b>1742</b>		<b>795</b>

TEQ = toxic equivalent derived from World Health Organization  
(van den Berg *et al.* 1998)

Results of the List 1 scan technique on the solid samples are shown in Appendix G, and summarised in Table 8.

**Table 8 Summary of List 1 screening technique results for MSWI solid residues**

Bottom Ash	untreated			carbonated		
	BA 1	BA2	BA3	BA1	BA2	BA3
No. of compounds reported	29	56	54	17	44	15
Typical range (mg/kg)	most <1	13>10	many>100	Most<1	most<1	
	all <10	several at several 10s	10>500	All<2		all<10
Maximum (mg/kg)	6.8	89	4,000	1.6	1.2	5.4
<b>APC residues</b>						
	<b>APC1</b>	<b>APC2</b>	<b>APC3</b>	<b>APC1</b>	<b>APC2</b>	<b>APC3</b>
No. of compounds reported	24	73	45	3	7	2
Typical concentrations (mg/kg)	most<1	most 1-10	most 1-10	<0.5	<1	<1
		5>50	7>10			
Maximum (mg/kg)	15	144	46	0.4	2.0	0.8

### 3.2.1 Bottom ash

Analyses for inorganic and conventional parameters in the untreated wastes are similar to those reported elsewhere for bottom ash. In particular, they are of a similar magnitude to those found in a previous study of residues from incinerators in England and Wales (Environment Agency, 2002) and in an earlier study for the Energy Technology Support Unit (ETSU, 1996).

Loss on ignition (Lol) was 1.5% to 3.3%. This is typical of the performance expected from modern incinerators. The effect on these Lol results of the removal of unburnt paper during the sieving process can not be gauged: sieving also removed other oversize particles and objects, with low organic content.

The predominant heavy metals were Zn, Cu and Pb.

Moisture content was in the range 18% to 22%.

Carbonation, as might be expected, had no significant effect on the elemental composition. The carbonated materials had slightly increased Lol at 2.5% to 5.3%. This may be due to decomposition of carbonate. One metal result (Cu, Site 1) on the carbonated samples is anomalous, showing an increase to 43,000 mg/kg and is considered likely to be due to an analytical error.

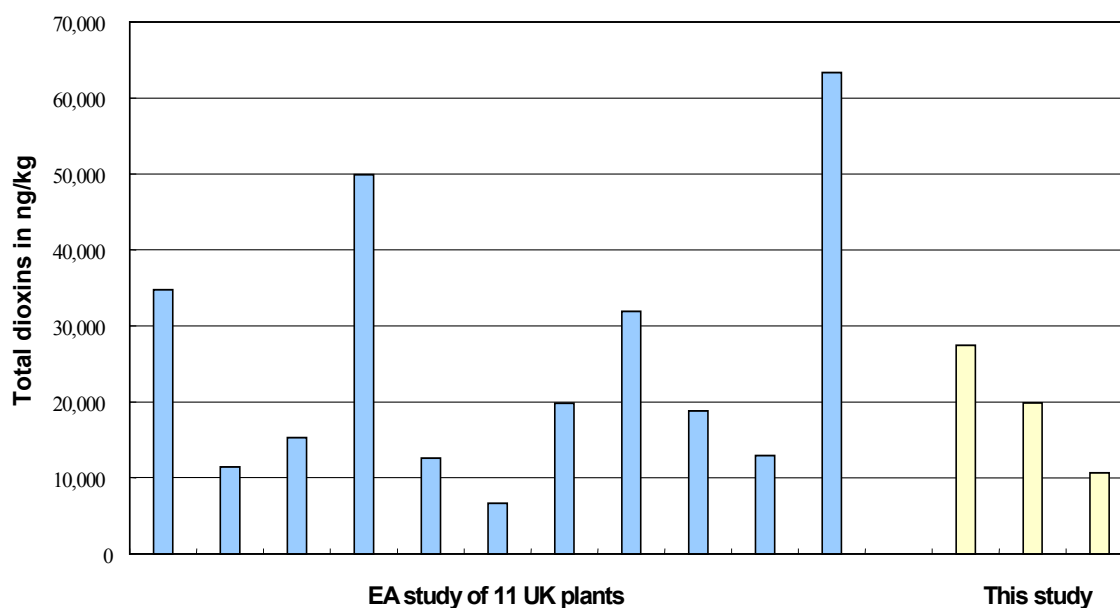
Dioxin levels in the untreated bottom ash were very low (see Table 6): only one congener was detected, in only a single sample. Slightly higher levels were reported in the carbonated samples, but were still only in the range 5 to 12 ngTEQ/kg. These results are comparable to the range 0.64–23 ngITEQ/kg found in a previous study of UK bottom ashes (Environment Agency, 2002).

The results of the List 1 screening technique are summarised in Table 8. They revealed the presence of large numbers of trace organic compounds in some samples, with orders of magnitude differences in concentration between sites. Individual compounds were detected at more than 1,000 mg/kg at Site 3, and less than 10 mg/kg at Site 1. The majority of the substances detected were chlorinated aliphatic and aromatic hydrocarbons plus some BTEX, alkenes and PAH (see Appendix G). Carbonation led to a massive fall in concentrations, with all three sites having similarly low levels (most <1 mg/kg; all <10 mg/kg) and fewer compounds detected. This behaviour is in contrast to the dioxin results, which were higher, overall, after carbonation. The reduction in the trace organics is likely to reflect their volatility and hence removal during drying and carbonation.

### 3.2.2 APC residues

The conventional, inorganic and heavy metal results for APC residues (Table 5) were as expected. The high Ca and Cl content (~26% and ~16%) reflect the incorporation of lime used in the semi-dry scrubbing process and its partial conversion to calcium chloride by HCl gas. The heavy metal concentrations were similar to those found during a previous study of UK incinerators (Environment Agency, 2002), with Zn, Pb and Cu predominant. Cd was also significantly enriched compared with the bottom ash. Loss on ignition was very low, and, as with the bottom ash, it was higher in the carbonated samples.

Dioxin concentrations found in this study are compared in Figure 4 with those found in a previous study of UK incinerators (Environment Agency, 2002). The totals found at the three plants in this study were within the range found in the larger UK study.



**Figure 4 Comparison of total dioxin content of solid APC residues in this study compared with earlier EA study of 11 UK incinerators**

The relative dominance of individual congeners was very similar at all three plants in this study, with the same two congeners comprising at least 50% of the TEQ (toxic equivalent), in each case, namely 2,3,4,7,8-PCDBF and 1,2,3,7,8-PCDD.

Carbonation had no significant effect on total dioxin concentrations. For Site 1, the total (in ng TEQ/kg) was approximately halved after carbonation. This anomaly is due to one congener with a high TEQ factor, namely 2,3,4,7,8-PCDBF. Given the absence of any significant decrease in other congeners, in any of the APC or bottom ash samples following carbonation, it is possible that this is an analytical or transcription error.

Trace organics (Appendix G and Table 8) varied widely in the number of compounds detected and the concentrations recorded. Numbers and concentrations were broadly similar to the range found in the bottom ash, except that the extreme high values in BA3 did not occur in APC3. The compounds detected in the untreated APC residue were mainly chlorinated aliphatic and aromatic hydrocarbons, similar to those in the bottom ash. PCBs and hexachlorobenzene were also detected at low concentration in the samples from Site 2. Following carbonation, the number of compounds, and their concentrations, fell even more dramatically than they did with the bottom ash. Very few compounds were detectable and concentrations were extremely low, mostly less than 1 mg/kg.

### 3.3 Results of leaching tests on bottom ash

All analytical results, for bottom ash and APC residue, are given in appendices as follows:

Appendix H:	major ions, sanitary parameters and heavy metals
Appendix I:	dioxins and furans
Appendix J:	List 1 screening method results for aqueous eluates
Appendix K:	List 1 screening method results for acid leaching test eluates
Appendix L:	List 1 screening method results from column leaching tests.

There was generally very good consistency between replicates, for nearly all parameters. This can be seen in graphical presentations of data in the following sections of the report.

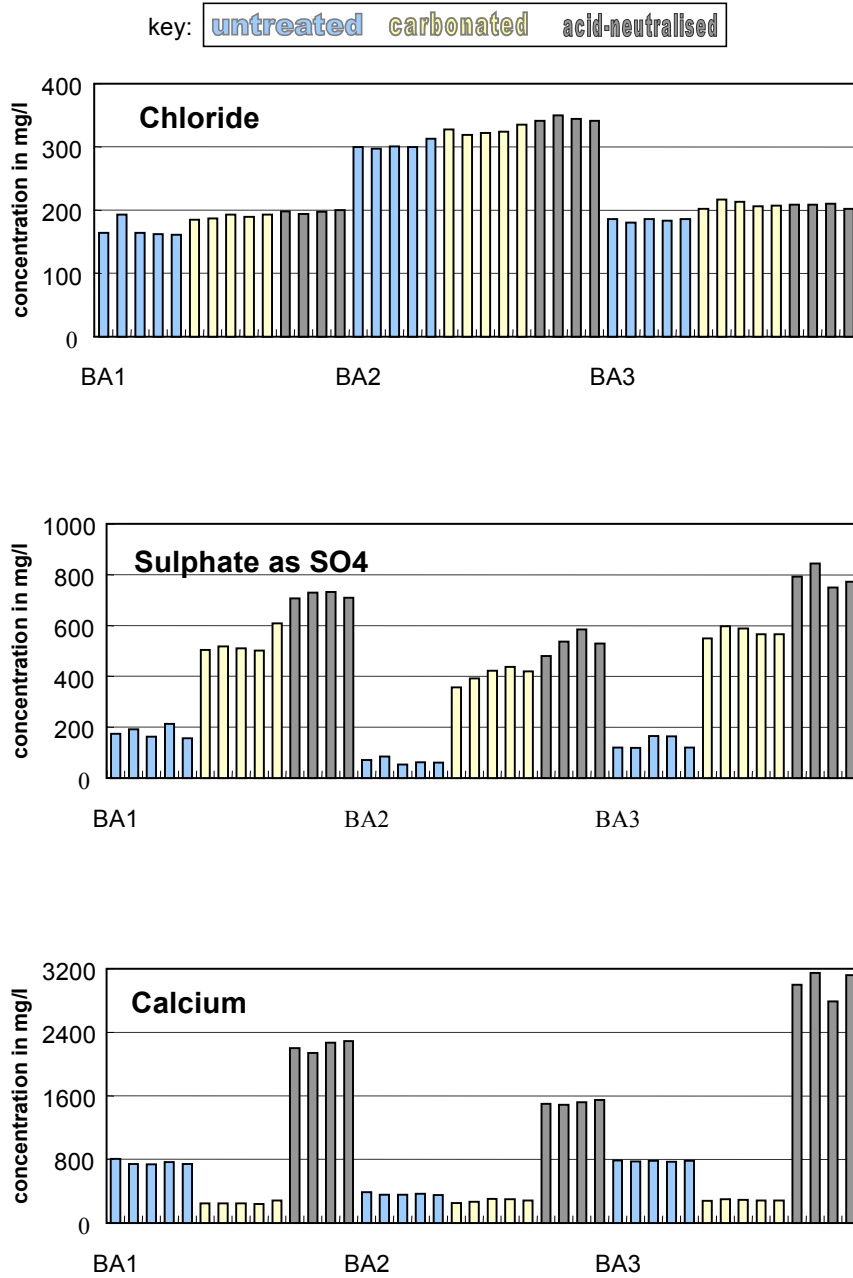
The few exceptions were:

- A small number of COD, Ca and SO<sub>4</sub>, results exhibited greater variability;
- Some heavy metals, notably Ba, Mo, Hg and Se, exhibited greater spread, mostly at high pH values in the results for untreated APC residue.

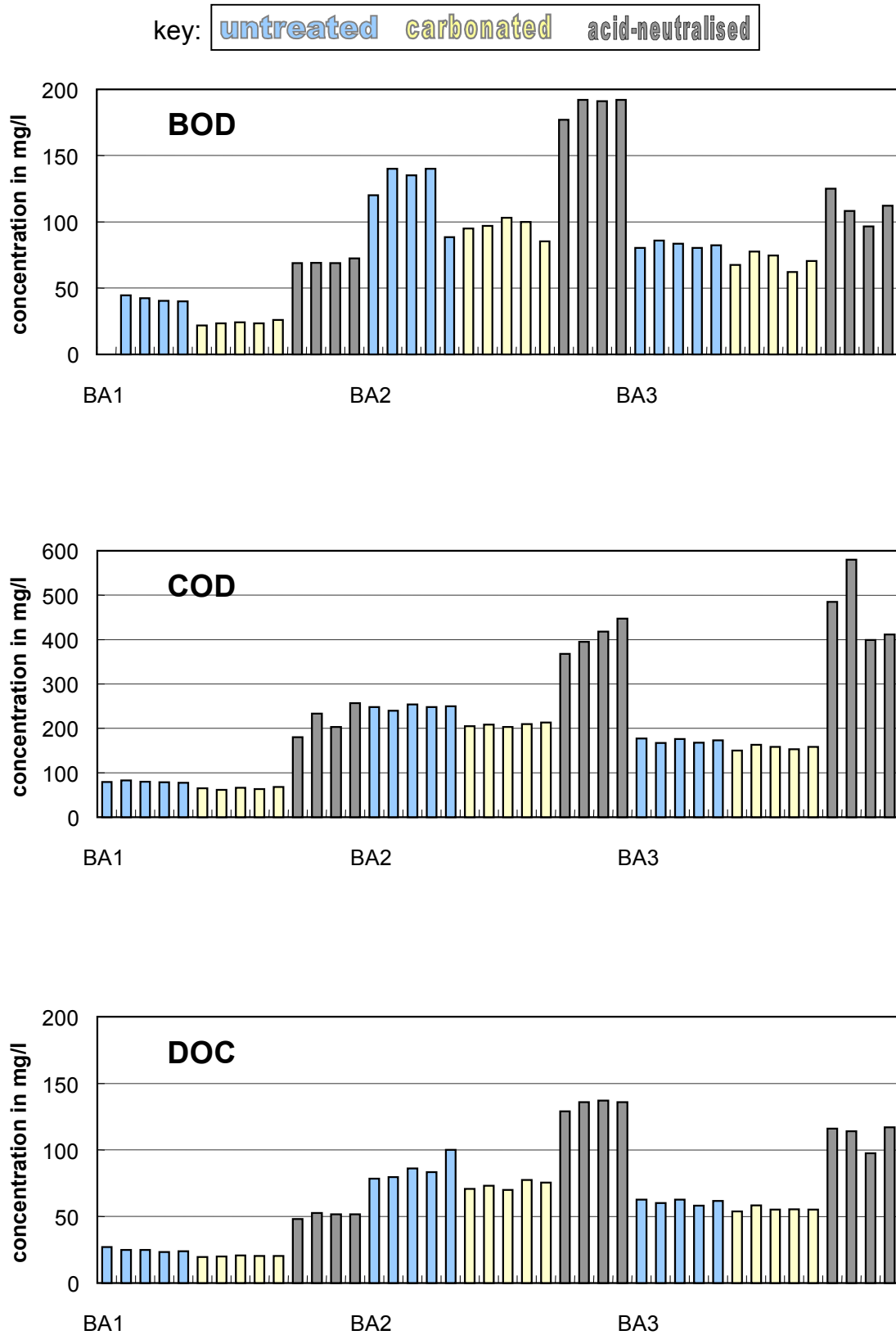
No results were received for Fe, Mn or Al in any of the eluates. Results for some other parameters were not received for certain samples. This applied to TKN, BOD and alkalinity. For other parameters, namely DOC (dissolved organic carbon), COD, BOD, Cd and some other metals, the detection limits were often so high as to limit the usefulness of the results.

#### 3.3.1 Results for bottom ash at LS 10: conventional parameters

Eluate concentrations for Cl, SO<sub>4</sub>, Ca, BOD, COD, DOC, pH, NH<sub>4</sub>-N and TKN are shown as bar charts in Figures 5 to 7. The charts allow direct comparison between replicates, between treatments (untreated, carbonated, and acid-neutralised) and between sites. Eluate concentrations of heavy metals are shown in Figure 8, graphed against pH value. Note that Figures 5 to 8 show concentrations in the LS 10 eluates rather than quantity leached per unit weight of ash. This format has been used because the focus of this study is leachate quality rather than characterisation of the wastes.

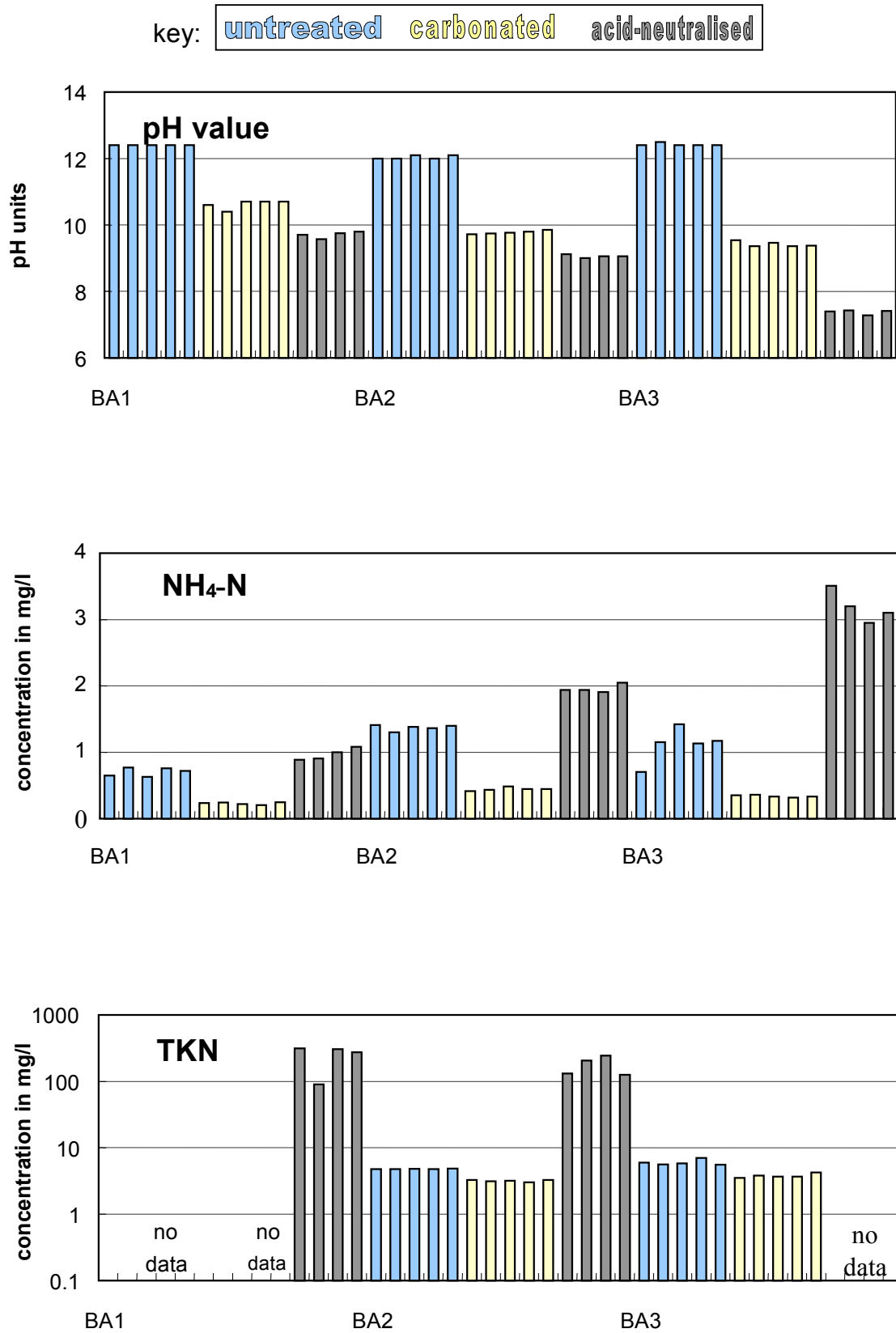


**Figure 5** Concentrations in LS 10 eluates from MSWI bottom ash replicates (1 of 3)



**Figure 6** Concentrations in LS 10 eluates from MSWI bottom ash replicates (2 of 3)





**Figure 7** Concentrations in LS 10 eluates from MSWI bottom ash replicates (3 of 3)

The eluate concentrations of major ions, DOC and heavy metals in the aqueous tests on untreated bottom ash were very similar to the ranges found in other studies in the EU at LS 10. An example comparison is shown in Table 9. This similarity confirms that the bottom ashes in this study have similar chemical characteristics and behaviour to those in other EU countries. They are therefore a valid basis for a generic assessment of the impact of carbonation and acid treatment on leachate characteristics. This is as expected and is consistent with views expressed by EU experts, that bottom ash characteristics and behaviour are very similar across the EU, for residues from modern MSW incinerators.

**Table 9 Comparison of aqueous eluate concentrations from untreated MSWI bottom ash, with results from another EU study (van der Sloot *et al*, 2000)**

	van der Sloot <i>et al</i> (2000)*		This study, eluate
	leachable at LS 10 (mg/kg)	∴ eluate (mg/l)	(mg/l)
Na	2000–2500	200–250	70–200
K	700–900	70–90	70–110
Ca	1000–2000	100–200	350–800
Cl	data not given		160–310
S	60–500	6–50	–
		(= 20–150 as SO <sub>4</sub> )	50–200
DOC	300–400	30–40	25–75
As	<0.01–0.1	<1–10 µg/l	<1
Cr	0.06–0.2	6–20 µg/l	6–68 µg/l
Cd	0.001–0.01	0.1–1 µg/l	<1 µg/l
Cu	3–10	0.3–1	0.5–1.3
Ba	2.5–10	0.25–1	0.6–0.7
Mo	0.3–0.5	0.03–0.05	0.05–0.07
Ni	0.01–0.07	1–7 µg/l	<5–30 µg/l
Sb	0.01–0.1	1–10 µg/l	<10–15 µg/l
V	0.004–0.03	0.4–3 µg/l	<10 µg/l
Zn	0.3–2.5	0.03–0.25	0.2–1.0
Pb	1–8	0.1–0.8	1–4

\*Data from this reference have been estimated from log-scale graphs and are therefore approximate only. However, this is adequate for the general comparison of characteristics.

The eluates from the untreated bottom ash were strongly alkaline, with pH values of 12.0 to 12.4. Carbonation reduced this range to ~9 to 10.5. This is not as low as the value of 8.3 expected from calcium carbonate, and indicates that carbonation was variable and incomplete. The eluates from acid treatment had lower pH values, spanning a range of two pH units, from ~7.5 to ~9.5, despite the efforts to achieve a target pH of 8.3.

Leachable major ions from the untreated ash were dominated by similar concentrations of chlorides, sulphates and hydroxides of Ca, Na and K, in the untreated wastes. The two treatments had little effect on Cl, Na or K. However, Ca and SO<sub>4</sub> leaching were strongly affected, in different ways:

- carbonation led to reduced leaching of Ca by ~50% (to ~200–300 mg/l) and increased leaching of SO<sub>4</sub> (to ~400–600 mg/l).
- acid treatment also increased the leaching of SO<sub>4</sub>, to an even greater extent than carbonation (to ~500–800 mg/l). However, Ca leaching did not decrease, but increased dramatically, leading to its becoming by far the dominant cation (~1500–3000 mg/l).

The behaviour of Ca and SO<sub>4</sub> shows that the effects of the two treatments on the chemical matrix are different, regardless of their effects on pH, metals etc.

Acid treatment, as expected, led to the presence of NO<sub>3</sub> as the dominant anion (TON ~750–1200 mg/l), compared with virtually none in the untreated waste eluates. These concentrations were as expected from the volume of 2M HNO<sub>3</sub> added. However, the results for Site 3 were much lower (~9 mg/l) and are regarded as probably erroneous. The Site 3 samples were submitted in a different batch from Sites 1 and 2. They were submitted with APC eluates, which also had inconsistent and improbable TON results.

DOC concentrations from the untreated bottom ash varied by a factor of around three between sites, (~25 to ~75 mg/l) and correlated roughly with the Lol in the solid waste. The results for BOD (Figure 6) and COD indicated BOD/COD ratios of typically ~0.5. This suggests that a high proportion of the DOC may be readily degradable. Carbonation had no significant effect on the DOC concentration. There was a small reduction in the BOD/COD ratio at Site 1 but not at Sites 2 or 3. In contrast, acid treatment led to a large increase in leaching of DOC: concentrations were approximately doubled, to ~50–135 mg/l. This was accompanied by a small decline in BOD/COD ratio (range 0.24 to 0.46).

Acid treatment also led to a large increase in the reported concentrations of organic nitrogen. The untreated wastes produced eluate nitrogen concentrations typically of:

NH <sub>4</sub> -N	~1.5 mg/l
TKN	~5 mg/l
TON	<1 mg/l

Carbonation led to small reductions in the already low eluate concentrations of NH<sub>4</sub>-N and TKN (Figure 7). However, acid treatment produced reported eluate concentrations of:

NH <sub>4</sub> -N	1 to 3 mg/l
TKN	180 to 250 mg/l

The apparent high level of organic nitrogen in these eluates is difficult to reconcile with the DOC concentrations. These levels would imply the existence of organic compounds containing a very high proportion of nitrogen, and must be regarded as questionable. This does not appear to be simply an effect of lower pH values: for example, the Site 2 acid eluates had similar pH values to the Site 3 carbonated eluates but had far higher TKN concentrations (see Figure 7).

The heavy metals present at the highest concentrations in the eluates from untreated bottom ash were:

Pb	1 to 4 mg/l
Cu	0.5 to 1.3 mg/l
Zn	0.2 to 1 mg/l
Ba	0.6 to 0.7 mg/l
Mo	50 to 70 µg/l

Many of the other metals were at or below their detection limits in most replicates (As, Cd, Tl, Se, Sb, Sn, V, Hg) from untreated bottom ash.

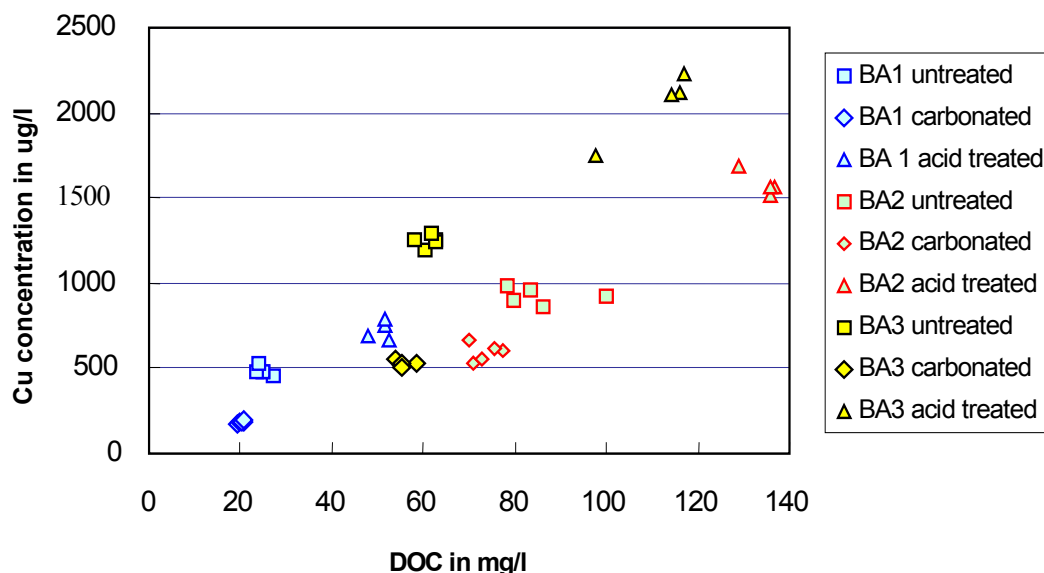
The effect of the two treatments on metals was highly variable. Leaching of some metals was improved (i.e. reduced) by both treatments and some worsened by one or both treatments:

- improved: Pb, Zn (depending on pH), Ba
- worsened: Sb, Cd, V, Mo, Cr, Se, As

The effects of the two treatments on metal leachability was highly variable. The results are summarised in Table 10 and Figure 8 and are discussed below:

- Leaching of Pb and Zn was generally reduced by more than two orders of magnitude. Both metals are amphoteric and this can be seen in the high concentrations leached at high pH values (Figure 8). For Site 3, the lower than intended pH resulting from the acid treatment led to a dramatic increase in leaching of Zn.

- Leaching of Cu was slightly improved (reduced) by carbonation but was worsened (increased) by acid treatment. This is unlikely to be a simple pH effect: the acid treatment released higher concentrations of DOC. There is a reasonably strongly correlation between copper concentrations and DOC. This is shown in Figure 9. This has been noted previously by van der Sloot *et al.* (2000) who considered that organic complexation was an important control over Cu leaching from bottom ash.

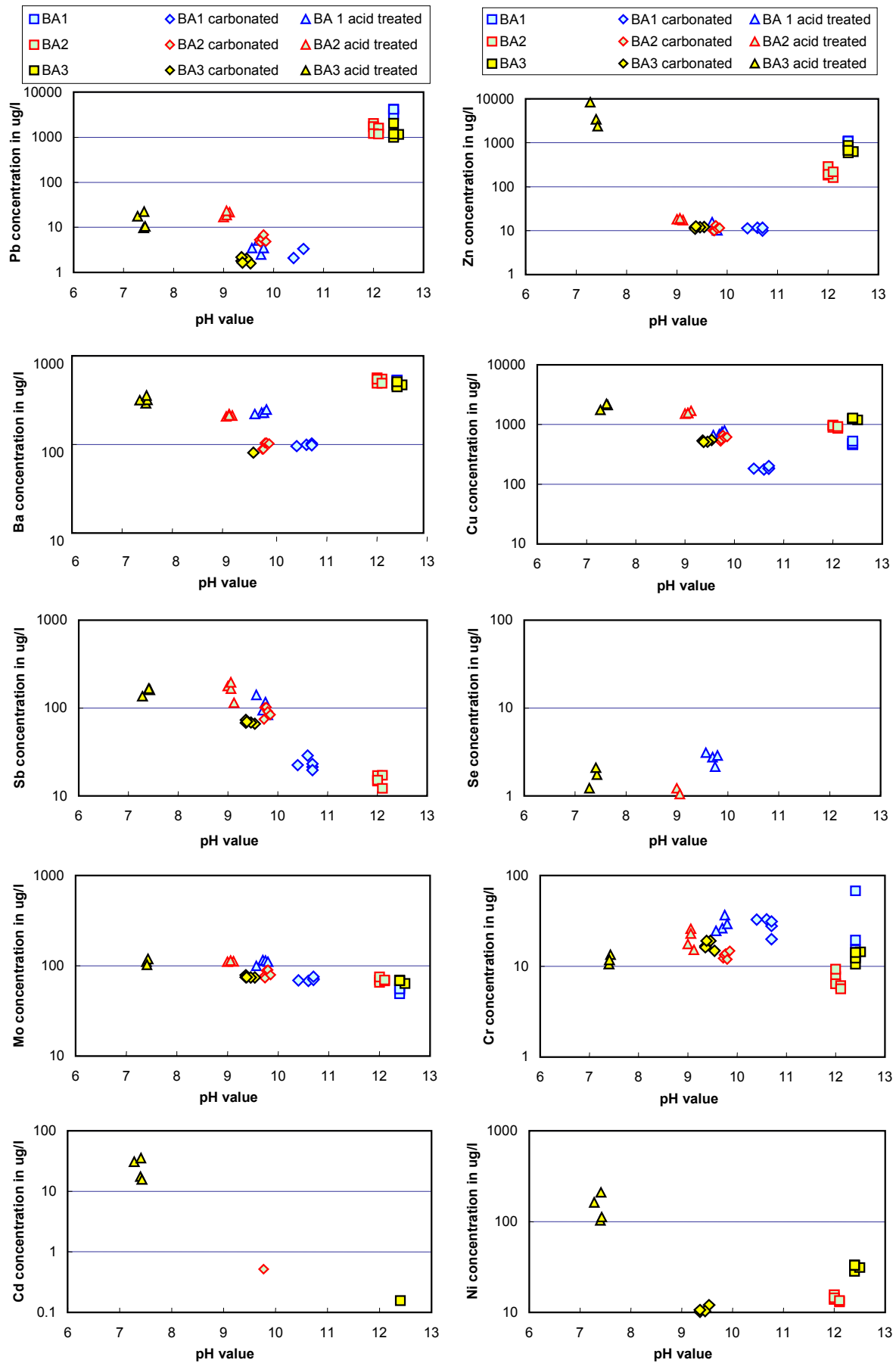


**Figure 9** Correlation of copper and DOC concentrations in LS 10 eluates from MSWI bottom ash

- Cr leaching was hardly affected by either treatment.
- Mo and Sb appeared to have a fairly consistent relationship with pH value, both increasing as the pH fell, and therefore both slightly worsened, along with V, by both treatments.
- Some metals were only detectable in the acid-treated eluates, namely Cd, Se and As.

**Table 10** Effects of carbonation and acid treatment on metal leaching from bottom ash (Full results in Appendix H)

	Units	Concentration in LS 10 eluate		
		untreated	carbonated	acid-treated
Pb	µg/l	1,000–4,000	<1–6	2–20
Cu	mg/l	0.5–1.3	0.2–0.6	0.7–2.2
Zn	µg/l	200–1,000	~10	10–11,000
Ba	mg/l	0.6–0.7	~0.1	0.25–0.4
Mo	µg/l	50–70	70–90	100–110
Cr	µg/l	6–20	12–30	10–35
Sb	µg/l	≤10–15	20–100	100–200
Cd	µg/l	<1	<1	<1–35
V	µg/l	<10	<5–18	10–45
Se	µg/l	<1	<1	1–3
As	µg/l	<1	<1	<1–4



**Figure 8** Metal concentrations in LS 10 eluates from MSWI bottom ash

### 3.3.2 Results for bottom ash column leaching studies

Data for inorganic, sanitary parameters and heavy metals are shown in Table 11. The approximate ranges found in the LS 10 eluates are included for comparison.

**Table 11 Analysis of column test eluates on bottom ashes, for inorganic ions, sanitary parameters and heavy metals**

Determinand	units	Site 1 untreated BA	Site 2 untreated BA	LS 10 untreated BA range	Site 2 carbonated BA	Site 2 carbonated BA
		column test	column test	LS 10 test	column test	LS 10 test
pH	pH units	12.4	11.2	12.0-12.4	7.43	9.8
Conductivity	uS/cm	15500	7750	4000-8000	12500	1900
DOC	mg/l	360	578	25-75	115	75
COD	mg/l	956	1560	80-250	441	210
BOD	mg/l	449	904	40-140	81.3	95
NH <sub>4</sub> -N	mg/l	11	12.3	~1.5	2.42	0.45
TKjN	mg/l	32.3	38.6	~5	10.1	3.2
CN (total)	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005
Na	mg/l	978	1070	70-200	1340	150
K	mg/l	977	669	70-110	604	85
Ca	mg/l	1010	227	400-800	1150	280
Mg	mg/l	<0.30	<0.30		24.8	<1
Cl	mg/l	2070	1530	160-300	3350	325
SO <sub>4</sub>	mg/l	452	38.9	50-200	1900	405
NO <sub>x</sub> -N	mg/l	0.288	0.637	<0.2-0.7	0.232	0.85
alkalinity pH4.5 as CaCO <sub>3</sub>	mg/l		896		79.9	170
<b>Total metals:</b>						
Fe						
Mn						
Al						
As	ug/l	<1.00	<1.00	<1	<1.00	<1
Hg	ug/l	<0.010	<0.010		0.012	<0.01
Cd	ug/l	0.936	1.11	<0.5	1.45	<0.5
Cr	ug/l	5.55	5.88	6-20	2.34	~13
Cu	ug/l	9840	5060	500-1300	1190	600
Pb	ug/l	4670	331	1000-4000	25.5	5.5
Ni	ug/l	80.2	67.1	<5-30	29.8	<5
Zn	ug/l	1310	56	200-1000	66.6	11
Sb	ug/l	<5.00	26.2	<10-15	61.4	90
Mo	ug/l	359	275	50-70	110	80
V	ug/l	<1.00	2.9	<5	1.38	<5
Ba	ug/l	449	1040	600-700	83.3	120
Tl	ug/l	<10.0	<10.0		<10.0	<
Se	ug/l	<1.00	<1.00		<1.00	<
Sn	ug/l	<250	<250		<250	<

### Untreated bottom ash

For several parameters, concentrations in the column eluates were in the range of approximately five to ten times higher than in the LS 10 eluates. This suggests that for these substances the leached quantity (in mg/kg) is similar at high or low LS ratio i.e. the substances are soluble and a high proportion is leached whether at low or high LS ratio. This group comprised:

Na, K, Cl, DOC, BOD, TKN, NH<sub>4</sub>-N, Cu, Mo, Ni

For Cu, this behaviour may simply reflect that of DOC.

For other parameters, concentrations in the column eluates were similar to those at LS 10. This indicates that their concentrations are equilibrium-controlled.

For Pb and Zn, concentrations are strongly pH-dependent but in the column eluates were similar to those at LS 10 for similar pH values.

### Carbonated bottom ash

The pH value from carbonated BA was only 7.43. This is not only much lower than in the LS 10 leachate, but also lower than would be expected from complete carbonation. It raises the question as to whether some additional buffering process developed in the carbonated material during the column test. Other inconsistencies in behaviour are also apparent, some of which may be related to the lower pH:

- DOC, COD, BOD, NH<sub>4</sub>-N and TKN were all much lower than in the eluate from the untreated Site 2 BA, whereas at LS 10 there had been only a slight difference between untreated and carbonated wastes.
- Ca, SO<sub>4</sub> and Mg concentrations were considerably higher from the carbonated column than from the untreated waste. At LS 10, carbonation had reduced leaching of Ca and only slightly increased leaching of SO<sub>4</sub>.

#### 3.3.3 Leaching of trace organics from bottom ash

Results for dioxins from the LS 10 tests are shown in Appendix I. Only a single congener was detected and only from one sample: Site 1 leached octachlorodibenzodioxin (OCDD) at 12.2 pg/l from the untreated ash and 7.2 pg/l from the carbonated ash. The congener OCDD had been detected at 105 ng/kg in the solid carbonated BA from Site 1, but was not detected in untreated waste. No other dioxin or furan was detected in any other sample. None were detected in any of the column eluates from bottom ash, untreated or carbonated.

Results from the List 1 screening method are shown in Appendices J (LS 10 aqueous eluates), K (LS 10 acid eluates) and L (column test eluates). Summary information is shown in Table 12. Key observations are:

- Fewer compounds were detected in the eluates than in the solid materials.
- Generally, the eluates contained between 5 and 20 compounds, at concentrations between 5 and 50 µg/l each.
- The type of compounds detected were also quite different: in the eluates the substances were predominantly aliphatic (C<sub>4</sub> to C<sub>12</sub>) and aromatic carboxy acids, ketones, aldehydes and alcohols and esters.
- With one exception, no List 1 compounds were detected and no halogenated compounds.
- The exception was the occurrence of benzene at a high concentration in the LS 10 eluates from Site 3. It was present at a similar concentration (3–4 mg/l) from both the untreated and carbonated material. However, it was not detected in the acid eluate. Site 3 had the greatest number and highest concentrations extractable from the solid bottom ash. However, benzene had not been one of the compounds detected.
- Carbonation had no noticeable effect on the number, type or concentration of substances detected in the eluates.
- The acid-treated eluates generally had slightly lower concentrations than the untreated waste eluates, but similar numbers and types of compounds detected.
- The number, type and concentrations of substances in the column test eluates was similar to those in the LS 10 eluates. This suggests that the concentrations are equilibrium controlled.

**Table 12 Summary of trace organic screening test results on eluates from bottom ash**

		No. of compounds detected	Eluates (µg/l)		Leachable (mg/kg)	
			typical	maximum	typical	maximum
<b>LS 10 eluates</b>						
1. Untreated	BA1	6	10–100	233	<1	2.3
	BA2	11	5–50	44	<0.5	0.4
	BA3	4	50–200	3,528*	<2	35*
2. Carbonated	BA1	12	20–100	234	<1	2.3
	BA2	11	20–100	230	<1	2.3
	BA3	24	20–100	4,182*	<2	42*
3. Acid-treated	BA1	6	4–6	26	<0.1	0.2
	BA2	18	4–20	48	<0.1	0.5
	BA3	12	2–10	52	<0.1	0.5
<b>Column test</b>						
Untreated BA1		9	5–50	700	-	-
Untreated BA2		25	5–50	800	-	-
Carbonated BA2		8	5–50	156	-	-

\*benzene

## 3.4 Results of leaching tests on APC residues

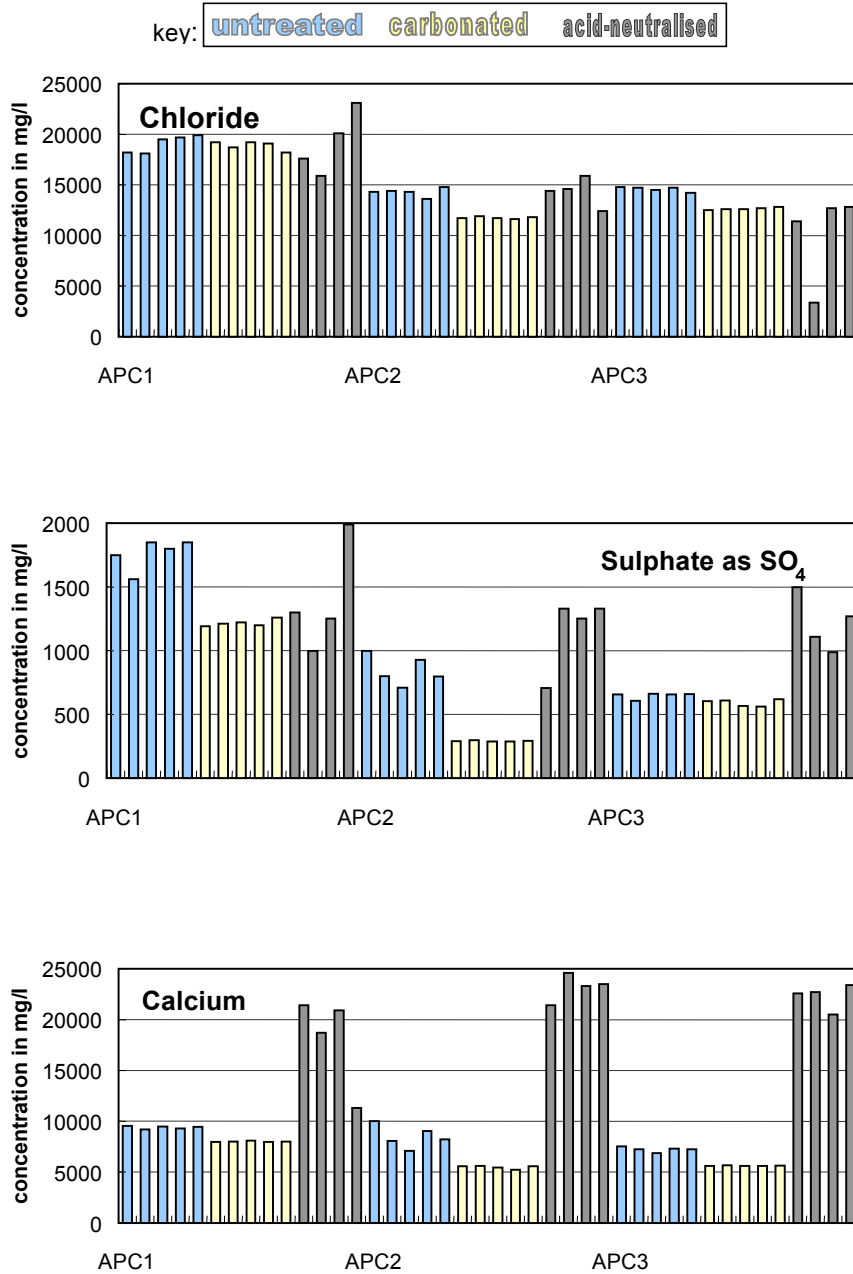
All analytical results are included in Appendices H to L as follows:

- Appendix H: major ions, sanitary parameters and heavy metals
- Appendix I: dioxins and furans
- Appendix J: trace organics in aqueous eluates
- Appendix K: trace organics in acid leaching test eluates
- Appendix L: trace organics in column leaching test eluates.

### 3.4.1 Results for APC residue at LS 10: conventional parameters

Eluate concentrations for Cl, SO<sub>4</sub>, Ca, BOD, COD, DOC, pH, NH<sub>4</sub>-N and TKN are shown as bar charts in Figures 10 to 12. The charts allow direct comparison between replicates, between treatments (untreated, carbonated, and acid-neutralised) and between sites. Eluate concentrations of heavy metals are shown in Figure 13, graphed against pH value. Note that Figures 10 to 13 show concentrations in the LS 10 eluates rather than quantity leached per unit weight of ash. This format has been used because the focus of this study is leachate quality rather than characterisation of the wastes.





**Figure 10** Concentrations in LS 10 eluates from MSWI APC residue replicates (1 of 3)

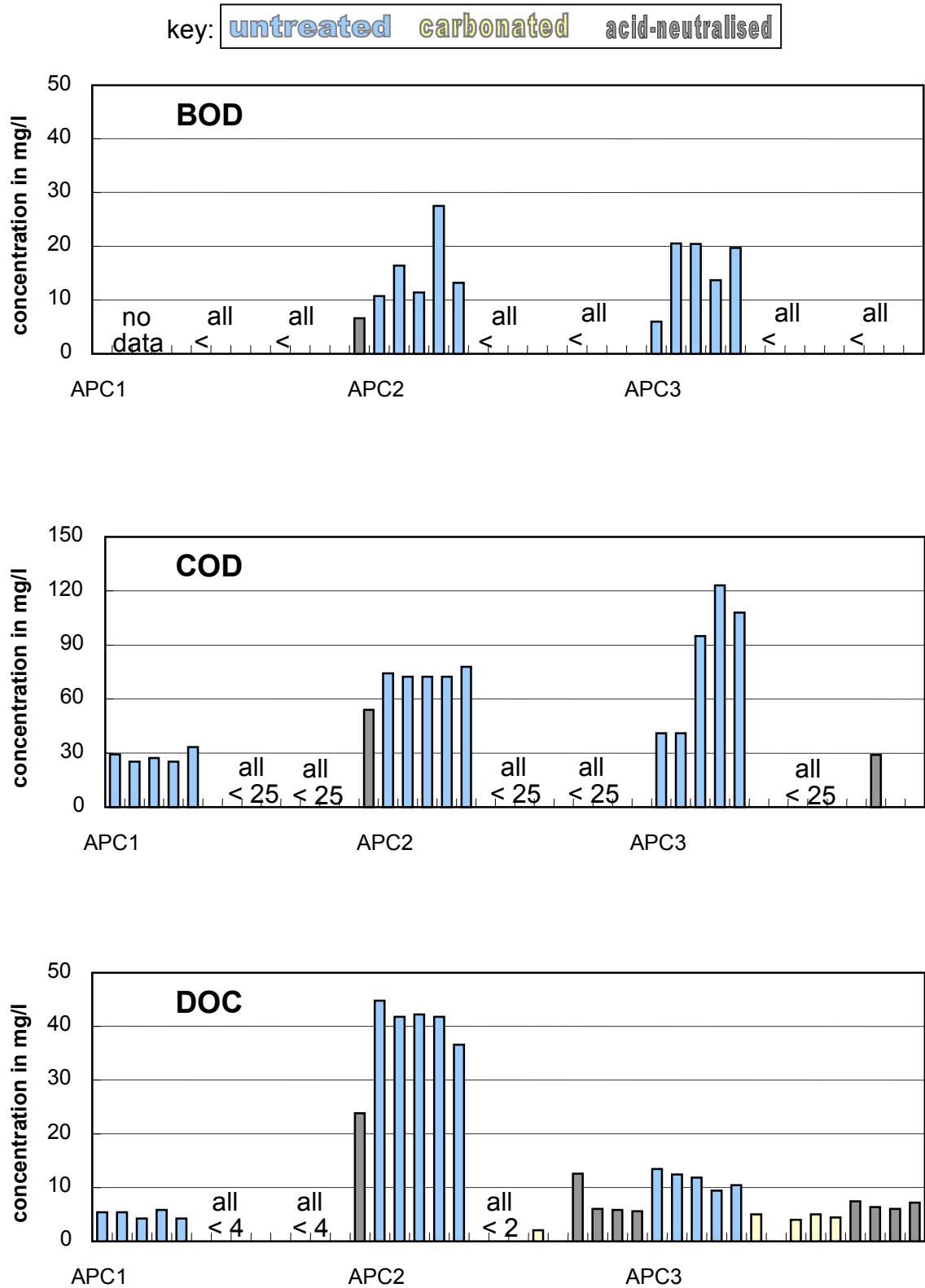


Figure 11 Concentrations in LS 10 eluates from MSWI APC residue replicates (2 of 3)

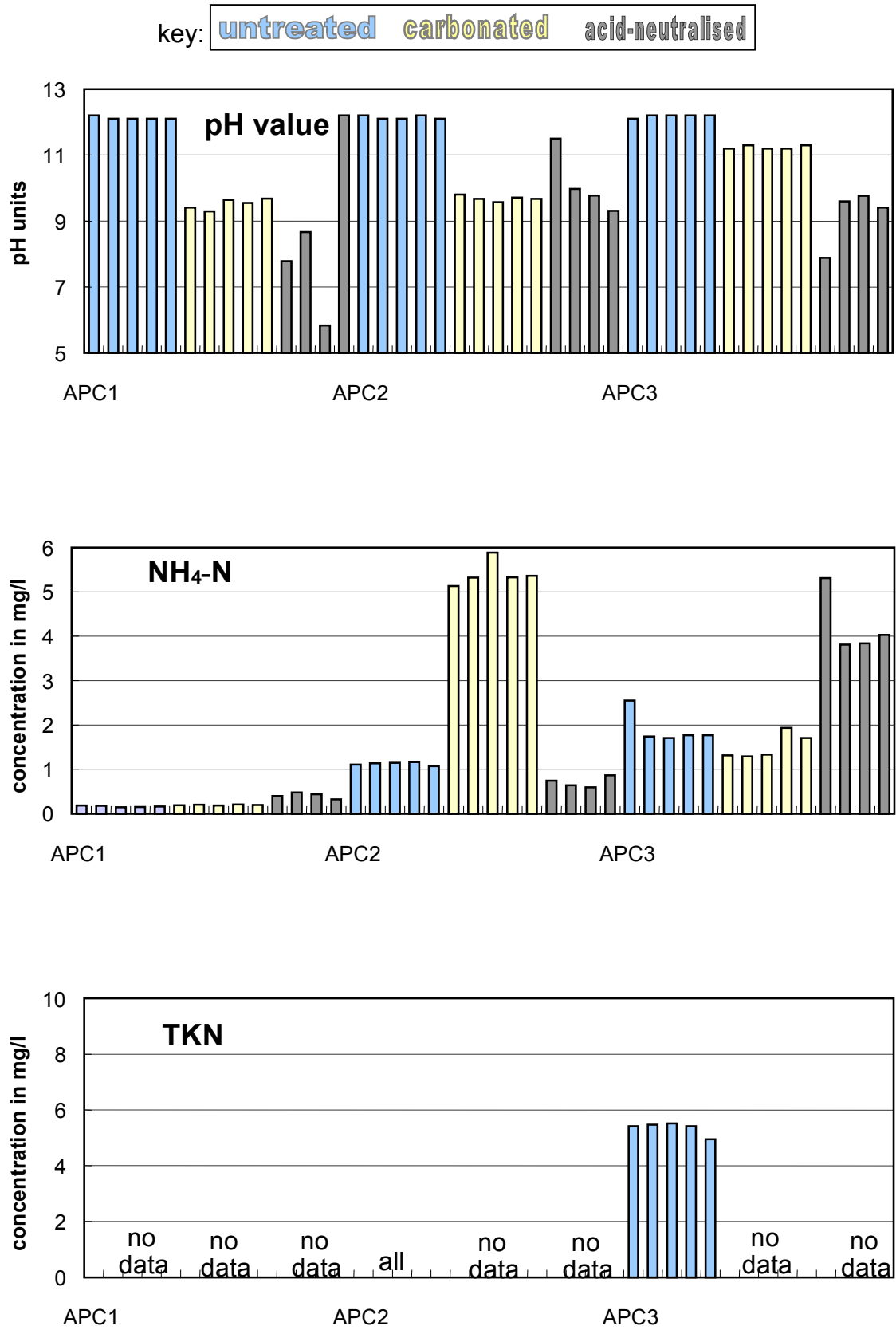


Figure 12 Concentrations in LS 10 eluates from MSWI APC residue replicates (3 of 3)

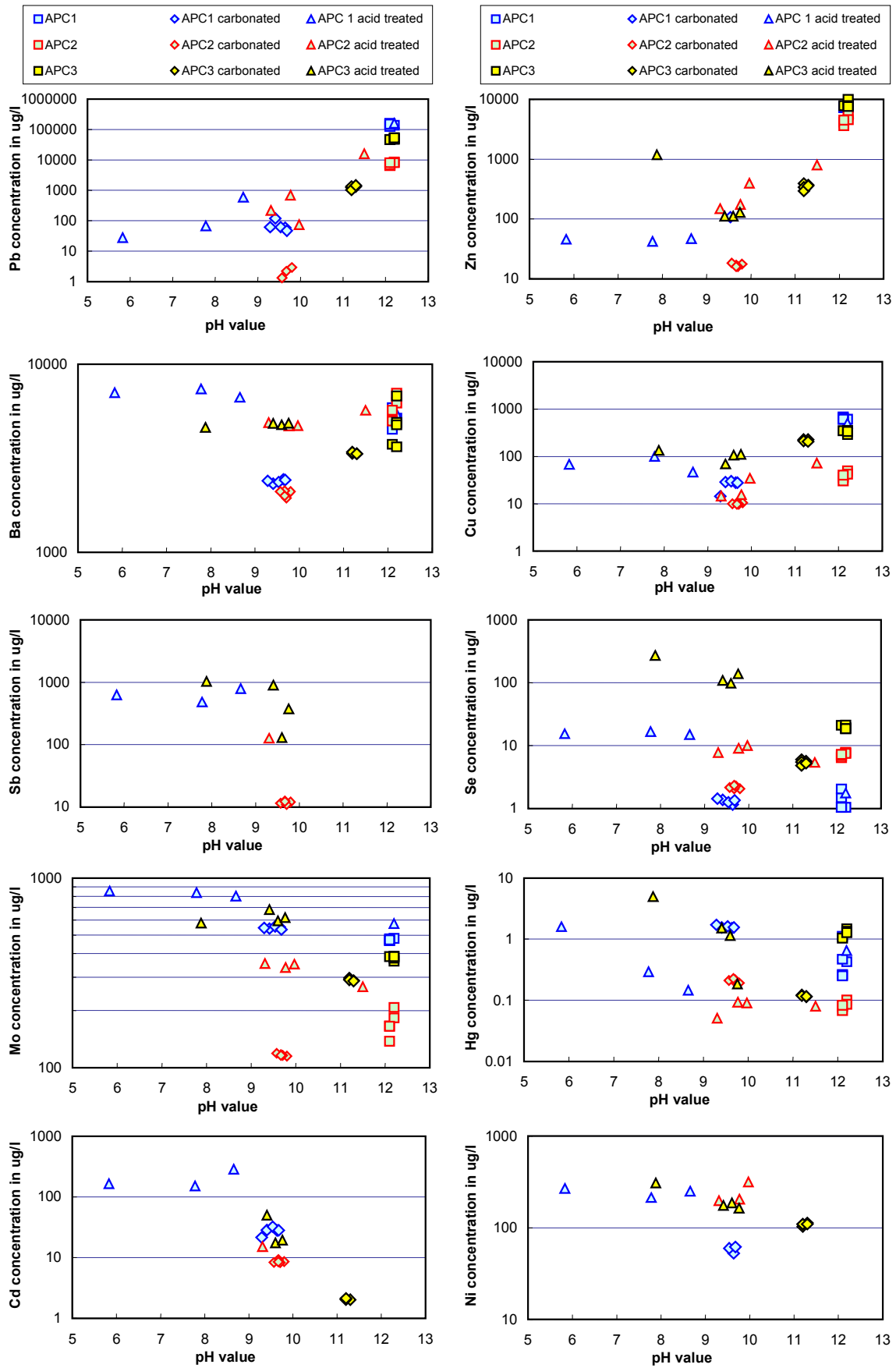


Figure 13 Metal concentrations in LS 10 eluates from MSWI APC residues

**Table 13 Comparison of aqueous eluate concentrations from MSWI APC residues, with results from another EU study (Abbas, 1998)**

	Abbas (1998)		This study, eluate
	leachable at LS 10 (mg/kg)	∴ eluate (mg/l)	(mg/l)
pH		12.64	12.1-12.2
Na	17300	1730	1220-1650
K	25200	2520	1580-2680
Ca	357000	35700	7200-9400
Cl	157300	15730	14000-19000
SO <sub>4</sub>	5400	540	650-1750
DOC			5-40
NH <sub>4</sub> -N			0.16-1.9
TKN			<1-5.3
		(µg/l)	(µg/l)
As	2.16	216	<1
Hg	0.036	3.6	0.1-1.3
Cr	0.00056	0.06	~11 <sup>1</sup>
Cd	0.160	16	<2-<100 <sup>2</sup>
Cu	64.7	6500	40-640
Ba	46.3	4600	4700-5900
Mo			170-470
Ni	0.96	96	<10-<500 <sup>2</sup>
Sb			<20-<100
V			<20-<100
Zn	36	3600	4500-8300
Pb	2869	287000	7600-144200

1. Results for Sites 1 and 2 had very high detection limits of 250 and 500 µg/l.

2. High and variable detection limits.

Eluate concentrations of major ions and heavy metals in the aqueous tests on untreated APC residue were similar to the ranges found in other studies in the EU at LS 10. An example comparison is shown in Table 13. This confirms that the APC residues used in this study have similar characteristics and behaviour to those in other EU countries. They are therefore a valid basis for assessing the effect of carbonation and acid treatment on eluate characteristics.

The eluates from the untreated APC residues in this study were strongly alkaline with pH values all in a narrow range of 12.1 to 12.2. Carbonation reduced the pH, though not as low as expected for calcium carbonate, and to a variable extent:

Site 1	9.3–9.7
Site 2	9.6–9.8
Site 3	11.2–11.3

It is assumed that Site 3 APC either had a higher free lime content or underwent a lesser degree of carbonation, than Site 1 and 2 APCs. The eluates from acid treatment also had lower pH values than the untreated waste eluates but exhibited greater variability between replicates. Note however, that for Site 1, the maximum and minimum pH values of 12.2 and 5.83 are thought to be due to an experimental error: one replicate probably received two additions of acid and the other none.

Leachable major ions from the untreated APC residue were dominated by Ca and Cl, as follows:

cations:	Ca	>> K	>Na
mg/l	~8,000	~2,000	~1,500
anions:	Cl	> SO <sub>4</sub>	> OH <sup>+</sup>
mg/l	~17,000	~1,000	~200

\* OH calculated from pH value.

Carbonation had little effect on the major ion concentrations (see Figure 10). Acid treatment resulted in greatly increased concentrations of Ca, and a slight increase in SO<sub>4</sub>, as follows (in mg/l):

	APC1	APC2	APC3
Ca	~18,100	23,200	22,300
SO <sub>4</sub>	1,384	1,154	1,217

It is assumed that most of the additional Ca was released from the neutralisation of lime by nitric acid.

The quantities of 2M HNO<sub>3</sub> added (see Appendix D for full details) should have led to TON concentrations of ~8,000 to ~12,000 mg/l. The reported concentrations of TON were very low, mostly at mg/l or tens of mg/l levels. These are considered to be erroneous. The possibility of some chemical reduction of NO<sub>3</sub> cannot be ruled out, as a partial explanation of the low TON results: a reaction of NO<sub>3</sub> with Al or Zn in alkaline solution is known to exist, which generates ammonia. (However, no significant elevation in NH<sub>4</sub>-N was observed.) The possibility of reduction to nitrogen gas by nascent hydrogen also exists. However, examination of ion balances on the results shows a large deficit of anions. This deficit is of a similar magnitude to the TON concentrations expected from the amounts of acid added.

DOC was one of a small number of parameters that showed large differences between the sites (others being reduced nitrogen species, Pb and Cu). Averaged concentrations of DOC in eluates from the untreated, carbonated and acid treated wastes were (in mg/l):

	APC1	APC2	APC3
untreated	5	41	11
carbonated	<4	≤2	4.6
acid treated	<4	7.5	6.8

The DOC was in general much lower than from bottom ash, as might be expected from the nature of the source. Only a limited number of BOD results were above the detection limit. These indicated BOD/COD ratios of ~0.22 in the eluates from untreated APC residue. This is lower than for the bottom ash and indicates that the DOC may be less readily degradable. In contrast to bottom ash, both treatments led to a decrease in leaching of DOC.

Concentrations of eluate NH<sub>4</sub>-N were low and variable. They showed no clear relationship between sites or response to treatment:

	APC1	APC2	APC3
untreated	0.16	1.12	1.9
carbonated	0.19	5.4	1.5
acid treated	0.41	0.71	4.2

TKN analyses were not reported for most of the APC eluates. The tentative inference from the two sets of results obtained (Sites 2 and 3, untreated waste eluates) were that organic nitrogen concentrations were very low, around 1–3 mg/l.

The heavy metals present at the highest concentrations in eluates from the untreated APC residues were, in decreasing order:

Pb > Zn ≈ Ba > Mo ~ Cu > Se

The concentrations in individual samples are shown graphically in Figure 13, plotted against pH. The ranges of concentrations in the untreated and treated eluates are summarised in Table 14.

**Table 14 Effects of carbonation and acid treatment on metal leaching from MSWI APC residues**

	units	concentration in LS 10 eluate		
		untreated	carbonated <sup>#</sup>	acid-treated*
Pb	µg/l	7,600–144,000	<1-120 [1,270]	<10–330
Cu	µg/l	40–640	10-30 [230]	30–100
Zn	µg/l	4,500–8,300	16-110 [390]	45–380
Ba	mg/l	4.8–5.9	2.1-2.4 [3.4]	4.8–7.0
Mo	µg/l	170–470	120-550 [300]	350–820
Cr	µg/l	10–<500	7-270 [90]	15–60
Ni	µg/l	<10–<500	50-<250 [110]	160–300
Sb	µg/l	<20–<100	10-<100	125–640
Cd	µg/l	<2–<100	8-30 [2]	15–650
V	µg/l	<20–<100	10-<100	<100
Se	µg/l	1–20	1-5 [5]	10–150
As	µg/l	<1	<1	1–7
Hg	µg/l	0.1–1.3	0.1-1.6 [0.12]	0.1–1.9

<sup>#</sup> maximum concentrations from APC3 (anomalous pH of 11.2) shown in square brackets.

\*results from samples with anomalous pH values have been omitted from this summary, where they were markedly different from results in the intended pH range

The most dramatic effects of treatment were on Pb and Zn: both treatments reduced eluate concentrations by one to three orders of magnitude. Leaching of some metals was worsened (increased) by the acid treatment. For some (Sb, Cd, V) a high proportion of results were below detection limits and only tentative comments, or no comments, can be made. The effects of the two treatments are summarised qualitatively below:

<b>Improved by treatment(s)</b>	Pb	dramatic	both
	Zn	dramatic	both
	Cu	modest	both
	Ba	slight	carbonated
	Se	slight	carbonated
	Cr	inconclusive	both
<b>Worsened by treatment</b>	Mo	slight	acid
	Sb	large	acid
	Cd	large-modest	both
	Se	large	acid
	As	large	acid

### 3.4.2 Results of column leaching tests on APC residues

Results for major ions, sanitary parameters and heavy metals are shown in Table 15, together with comparable data from the LS 10 tests. It is disappointing that so few results were available for organic carbon and nitrogen parameters: these were identified in the Phase 1 report as an area where existing data were sparse (Environment Agency, 2004a).

The column eluate pH values were lower by ~1 pH unit than in the corresponding LS 10 tests. This may indicate a degree of carbonation during the 9 day period of the column tests. Other mechanisms may also play a part. Evolution of gas, thought to be hydrogen, was observed from the two untreated APC columns. If this was generated by a reaction between fine metal particles and water, it would be

expected, if anything, to cause a rise in pH, due to the formation of metal hydroxides. No evolution of gas was observed from the carbonated APC residue.

For most parameters, concentrations in the eluate from the untreated APC2 column were lower than from untreated APC 1. For Ca, Zn and Se the difference was an order of magnitude or more, which is a much greater difference than occurred in the LS 10 tests.

There is no obvious explanation for these anomalies, particularly as results for some major components were reasonably close (e.g. Na, Cl, Ba, Pb). For NH<sub>4</sub>-N, the APC2 eluate had a much higher concentration than APC1, exactly matching their behaviour at LS 10.

The relationship between the column test and LS 10 eluate results has many similarities and some important differences compared with the bottom ash tests.

For the following parameters, concentrations in the column eluates were five to ten times higher than at LS 10:

Na, K, Cl, NH<sub>4</sub>-N, (Ca)

For Ca this applied to APC1 but not APC2, whose Ca concentration was actually lower than at LS 10. There are insufficient data for DOC, BOD, COD and TKN, but the limited information available suggests they may not have been significantly higher than in the LS 10 leachates. This is in contrast with the behaviour of bottom ash. Another contrast was the metals Cu, Mo and Ni. For these and most other components, concentrations in the column eluates were similar to those in the LS 10 eluates. This suggests that their concentrations were largely controlled by chemical equilibria rather than availability.

The absence of confirmed values for Cd in most of the eluates in this study is unfortunate: in the Phase 1 study, leachates from full-scale APC landfills typically had several tens to several hundreds of µg/l of Cd. The highest concentration in this study was 922 µg/l from the column test on carbonated APC1. This is comparable with field data and may be due to the lower pH (8.75) in this eluate. Nevertheless, the difference between this and 28 µg/l at pH 9.5 in the LS 10 eluates suggests either a very steep pH-solubility curve in this pH region or an additional mechanism affecting solubility.

Comparison of the column test results for APC1 before and after carbonation shows it had little effect on major ions and some metals (Mo, Se, Ba) but led to massive reductions in Pb and Zn, and a smaller reduction in Cu. This was also observed in the LS 10 tests.



**Table 15 Analysis of column test eluates on APC residues, for inorganic ions, sanitary parameters and heavy metals**

Determinand	units	Site 1 untreated APC residue	Site 2 untreated APC residue	LS 10 untreated APC range	Site 1 carbonated APC	Site 1 carbonated APC
		column	column	LS 10 test	column	LS 10 test
pH	pH units	11.1	11.4	12.1-12.2	8.75	9.5
Conductivity	uS/cm	183000	129000	43000-56000	167000	49000
DOC	mg/l	no result	<20	5-40		<4
COD	mg/l	no result	<52.0	30-80	71	<25
BOD	mg/l	no result	<5.70	~15	<5.70	<5.7
NH4-N	mg/l	1.94	17.2	0.15-1.9	1.47	0.19
TKjN	mg/l	<1.00	no result	<1-5	no result	no result
CN (total)	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005
Na	mg/l	9870	5260	1220-1650	8060	1550
K	mg/l	15500	5950	1580-2680	12500	2500
Ca	mg/l	46100	3330	7200-9400	45500	8000
Mg	mg/l	<10.0	<10.0	<1	<10.0	1
Cl	mg/l	98700	68200	14000-19000	91000	19000
SO4	mg/l	1320	586	650-1750	1270	1200
NOx-N	mg/l	no result	19.9	0.2-2	1.61	<0.2
alkalinity pH4.5 as CaCO3	mg/l	1040	688	~2500	31.2	15
<b>Total metals:</b>						
Fe						
Mn						
Al						
As	ug/l	<1.00	<1.00	<1	1.6	<1
Hg	ug/l	0.011	<0.010	0.1-1.3	0.041	1.6
Cd	ug/l	<5.00	<5.00	<2-<100	922	28
Cr	ug/l	<25.0	<25.0	~11	<10.0	250
Cu	ug/l	472	155	40-640	81.8	25
Pb	ug/l	21400	15000	7600-144200	397	70
Ni	ug/l	<25.0	<25.0	<10-<500	<10.0	55
Zn	ug/l	22200	1690	4500-8300	163	100
Sb	ug/l	<100	<100	<20-<100	<100	<100
Mo	ug/l	560	<100	170-470	819	550
V	ug/l	<100	<100	<20-<100	<100	<100
Ba	ug/l	32200	34100	4700-5900	17600	2400
Tl	ug/l	<50.0	<50.0	<20	<50.0	<100
Se	ug/l	41.1	5.31	1-20	43.8	1.3
Sn	ug/l	<250	<250	<50	<250	<25

The overriding impression from the data on APC residues in general, and the data in Table 15 in particular, is of unexplained inconsistencies in behaviour. A good example is Se, which gave the following results (concentrations in µg/l):

	APC1		APC2		Carbonated APC1	
	Se	pH	Se	pH	Se	pH
LS 10	1	12.1	7	12.1	1.3	9.3
column	41	11.1	5	11.4	44	8.8

Concentrations leached from APC1 appear unaffected by pH or by carbonation, but some factor in the column test led to a massive increase, far greater than might follow from the different LS ratios. In contrast, APC2 leached more than APC1 at LS 10, at identical pH, but actually leached less in the column test.

### 3.4.3 Leaching of trace organics from APC residues

Results for dioxins and furans are shown in Appendix I. No dioxin or furan congener was detected in any of the APC eluates, either at LS 10 or in the column test. Using the detection limits at LS 10, the total concentration of eluate dioxins can be estimated to be less than ~20 µg/l. The water leachable dioxin content was therefore less than 200 µg/kg or <0.2 ng/kg. This is less than 0.001% of the total dioxin content of the APC residue.

Results from the List 1 trace organic screening technique are given in Appendices J (LS 10 aqueous leaching test), K (LS 10 acid leaching test) and L (column leaching test). Summary information on the number of compounds detected and the range of concentrations is given in Table 16.

**Table 16 Summary of trace organics leached from APC residues, measured by List 1 screening technique**

	No. of compounds detected	Eluates (µg/l)		Leachable (mg/kg)		
		typical	maximum	typical	maximum	
<b>LS 10 eluates</b>						
1. Untreated	APC1	2	50	78	0.5	0.8
	APC2	1	22	22	0.2	0.2
	APC3	1	138	138	1.4	1.4
2. Carbonated	APC1	1	114	114	1.1	1.1
	APC2	2	24–134	134	0.2–1.3	1.3
	APC3	1	128	128	1.3	1.3
3. Acid-treated	APC1	2	5	6	0.05	0.06
	APC2	3	10	16	0.1	0.16
	APC3	2	4–22	22	0.04–0.2	0.2
<b>Column test</b>						
	Untreated APC1	5	10	84	0.1–0.8	0.8
	Untreated APC2	4	8–158	158	0.08–1.6	1.6
	carbonated APC1	1	34	34	0.3	0.3

The following observations may be made:

- Very few ( $\leq 5$ ) compounds were detectable in the eluates, whereas large numbers (several tens) of compounds were present in the solid materials.
- Eluate concentrations of those that were detected were typically in the range 10 to 150 µg/l.

- The type of compounds leached were completely different from those found in the solids. Substances in the eluates were mainly C<sub>5</sub>–C<sub>8</sub> ketones, alcohols and esters, all aliphatic. The screening technique detected no halogenated compounds, PAH, or BTEX compounds. None of the substances detected was a List 1 substance.
- Carbonation made no appreciable difference to the eluate concentrations but the eluate from acid treatment had, overall, ~80% lower concentrations. This may indicate that the substances eluted were solubilised at high pH. However, this would not be expected for most of the chemical types that were detected.
- The column test eluates contained more compounds (except for the carbonated sample) but the number was still small.
- Concentrations in the column test eluates were similar to those in the LS 10 eluates. This may imply substances that are controlled by chemical equilibria rather than availability.

# 4 Discussion

## 4.1 Suitability of the data obtained

The solids composition and aqueous LS 10 eluates from the wastes used in this study were comparable with data from other MSWI plants, both in the UK and other parts of the EU. The samples therefore form a suitable basis for assessing source term values, for considering the release of trace organics and for assessing the effects of treatment. Full achievement of these objectives was hampered by several factors:

- Difficulty in hitting the chosen target pH value with the acid treatment; values ranged over ~2 pH units and were generally higher than the intended 8.3.
- Missing results for some samples especially BOD, TKN and DOC for the APC residues and especially in the column tests.
- High and variable detection limits for some parameters, such as COD, DOC, BOD, TKN and some of the heavy metals. Cd was a notable example.
- Anomalous results for some parameters, such as low TON results on APC residues, and high TKN results on acid-treated bottom ash that were inconsistent with the DOC concentrations.
- Large differences between the sites, for certain parameters. An example was the solvent-extractable trace organics in bottom ash, and the occurrence of exceptionally high benzene concentrations in aqueous eluate from Site 3 bottom ash, but not in the other two sites.
- Inconsistency of the relationship between LS 10 data, column data (~LS 1) and field data from the Phase 1 study. These inconsistencies were particularly apparent for Se, Cd, TKN, pH, Ca and SO<sub>4</sub>, but also applied to a degree to several other parameters.

## 4.2 The release of trace organics

### 4.2.1 Bottom ash

Despite the presence of numerous halogenated compounds, BTEX PAH, phenols, etc. in the solid materials, virtually no List 1 trace organics leached from the bottom ash, with the following two exceptions.

A single dioxin congener, OCDD, was recorded in the LS 10 eluate from Site 1 BA, at a very low concentration: 12.2 pg/l from the untreated ash and 7.2 pg/l from the carbonated ash. None were found in the column test eluates or the LS 10 acid eluates. The WHO TEQ factor for OCDD is 0.0001, so the concentration as TEQ is insignificant. Although 24 hour LS 10 leach tests are not regarded as suitable for organics, the 9 day duration of the column tests gives added confidence that the dioxins strongly partition to the solid phase.

Benzene was recorded in the LS 10 eluates from Site 3 BA at levels of ~4 mg/l. This was an order of magnitude greater than for any other trace organic component. Although Site 3 BA had far higher solvent-extractable trace organics than the other two sites, benzene was not identified in the solvent extracts. The results cannot be dismissed lightly because it was recorded in the eluates from both untreated ash and carbonated ash. The source term values for bottom ash List 1 organics cannot therefore be established, or assumed to be 'absent' until further data is compiled.

The bottom ash eluates contained 500–1,000 µg/l of other identified trace organics. These were mainly aliphatic (C<sub>4</sub> to C<sub>12</sub>) and aromatic acids, aldehydes, ketones, alcohols and esters. None of these were halogenated compounds. This is a completely different chemical profile to the compounds extracted from the solids using dichloromethane. Individual compounds were typically present at 50 to 100 µg/l and included bisphenol A at two of the three sites: while not a List 1 substance, this has recently been added to the UK's Pollution Inventory reporting list for discharges to water.

The identified trace organics constituted only a small percentage of the DOC. This reached several hundred mg/l, and was almost doubled by acid treatment. The nature of >99% of the DOC is unknown. It has a high BOD/COD ratio, indicating that much of it would be readily degradable. It is also strongly correlated with leachable Cu concentrations, indicating that a portion of it has strong metal complexing capacity. The proportion of DOC with strong ligand properties, and its degradability, are unknown, although van Zomeren and Comans (2002) demonstrate around 20% of DOC as fulvic acid in fresh bottom ash, declining on weathering as pH decreases. The remaining DOC is made up of a small proportion of humic acids and around 80% as undifferentiated hydrophilic organic carbon fraction (*op. cit.*, 2002). Also unknown is the impact on the nature of the DOC, of prolonged storage in a landfill, where anaerobic biological activity may sometimes develop.

The Phase 1 study identified uncertainty over the concentration of organic nitrogen compounds in bottom ash leachates. The analytical data from the present study indicate perhaps 20 mg/l of organic N in leachate from untreated and carbonated BA. This would be approximately 4% of the DOC, which is slightly lower than the nitrogen proportion in the hard COD in conventional MSW leachates. The data from the acid treated bottom ash indicated a massive increase in leaching of organic nitrogen, to reach a C:N ratio of as little as 2:1 or less. It is very hard to envisage what compounds could be present that would have such a low C:N ratio and analytical error is suspected.

#### 4.2.2 APC residues

The dioxin content of the APC residues was much higher than in the bottom ash and was comparable with previous UK studies, at ~1,000–2,000 ngTEQ/kg. Despite this, no dioxin was detected in any of the eluates from any of the samples, either at LS 10 or from the column tests. This indicates that the dioxins in APC residues also strongly partition to the solid phase.

The trace organics identified with the List 1 screening technique were present at lower concentrations in the APC residue than in bottom ash, but were similar in their chemical nature, i.e. halogenated aliphatics and aromatics, BTEX, PAH. However, no List 1 compounds were identified in the eluates from any of the APC samples, either at LS 10 or from the column leachates. The compounds identified in the eluates were fewer in number and at lower concentrations than from the bottom ash. Leachable concentrations were up to ~150 µg/l, comprising not more than five components in any one sample. The substances were mainly C<sub>5</sub>–C<sub>8</sub> aliphatic ketones, alcohols and esters. This is a narrower range of substances than in the bottom ash eluates but falls within the same broad chemical groups. Like the bottom ash, it is a completely different group of compounds than those identified in the dichloromethane extracts of the solid waste.

Concentrations of DOC in the APC eluates were much lower than in those from bottom ash, by more than an order of magnitude, but the DOC also remains largely uncharacterised. There were insufficient results for BOD and COD to give any firm information on its degradability, though it appears likely to have a lower BOD/COD ratio than the DOC from bottom ash. TKN data were also incomplete. The organic nitrogen concentration appeared to be low (~1 mg/l) but, given the lower DOC (~20 mg/l) could have been a similar percentage of DOC to that in the bottom ash eluates. In contrast to the bottom ash, acid treatment did not increase the leaching of either DOC or organic nitrogen from the APC residues.

Cu concentrations in the APC eluates did not show any clear correlation with DOC. This suggests that the strong ligands leachable from bottom ash are not present (or at least not leachable) in the APC residues.

## 4.3 Effect of the two treatments on leachate quality

Acid treatment led to large increases in eluate concentrations of TON (nitric acid used), Ca, conductivity and TDS in both types of waste. Acid treatment and carbonation led to some increase in SO<sub>4</sub> leaching from bottom ash, but not from APC residues. Carbonation led to a slight increase in Ca leaching from bottom ash, but not from APC residue. There were no other significant impacts on leaching of major ions.

Sanitary parameters were only slightly affected by carbonation – APC residues exhibited some decrease in leaching of organic indicators – whereas acid treatment led to greatly increased leaching of DOC and organic nitrogen from bottom ash, as discussed above.

The main impact of both treatments was on pH and the leaching of metals. The effects on metals were not necessarily due entirely to the reduction in pH that resulted from the treatments:

- As expected, both treatments reduced the eluate pH values but not to the same extent.
- The treatments had a strong beneficial effect on most of the heavy metals that were leachable at the highest concentrations from the untreated waste, namely:

Pb, Zn, Ba from bottom ash

Pb, Zn, Cu from APC residue

- The most obvious exceptions to these generally beneficial effects were:
  - Cu, leachable at high concentration from bottom ash, and controlled by organic complexation, which was worsened by acid treatment;
  - Mo, leachable at moderate concentration from both materials, was generally slightly worsened by both treatments;
  - acid treatment worsened the leaching of trace concentrations of Sb, Se, As and V;
  - carbonation worsened the leaching of trace concentrations of Cr, Sb and V from bottom ash;
  - Ba, leachable at high concentration from APC residue, was unaffected by acid treatment and slightly reduced by carbonation.
  - Cd, leachable from APC residues at higher concentrations after both treatments.

One significant advantage of carbonation over acid neutralisation is the reduction in pH without loss of buffering capacity due to precipitation of calcite (Astrup *et al.*, 2001).

### 4.3.1 Impact of treatment on achieving Waste Acceptance Criteria

From this study it is inferred that the untreated APC residues would fail to meet acceptance criteria for hazardous waste landfill for Pb and Cl. Carbonation alone will bring leachable Pb concentrations for APC residues to well below acceptance criteria for stable, non-reactive hazardous waste. However, it is interesting to note that Sb may not comply with acceptance criteria for stable, non-reactive hazardous waste. This effect is even more pronounced for acid neutralisation where Sb exceeds this limit, and for some APC replicates exceeds the criteria for hazardous waste. The data for Cd are inconclusive, but indicate that any treatment method that results in a pH reduction may increase its mobility.

Other researchers have used pre-wash steps to remove soluble salts and, in some cases combined this with carbonation and/or phosphate addition to immobilise Pb (e.g. Hjelmar *et al.*, 2000, 2001). Cement stabilisation has a long history of use in a number of countries for treating APC residues to produce low permeability waste forms, particularly in the USA and France (Environment Agency, 2004b). However, limited leachate data is available from landfills that have accepted cement stabilised wastes. Environment Agency (2004a) includes limited data on composite leachate quality from one landfill site (Site G) that accepted cement stabilised hazardous wastes, including fly ash and APC residues.

Treatment may have an impact, not only on the ability to accept wastes at a particular class of landfill, but also on the timescales required to achieve stabilisation. It is for this reason that carbonation, converting a metastable mineral assemblage to one that is geochemically stable, is a potentially attractive treatment option for alkaline inorganic wastes. This has the added advantage, for example over acid neutralisation, of causing a significant reduction in pH without loss of acid neutralising capacity; thereby buffering pH, and controlling the solubility of some metals, for significant timescales (e.g. Astrup *et al.*, 2001).

## 4.4 Effect of weathering of ash in a landfill

The processes that operate in ash landfills are chiefly the result of intrinsic chemical reactions and the infiltration of rainwater and air. Current landfill design and operation is such that water infiltration is minimised using temporary and final low permeability covers. This results in low liquid to solid ratios, even during the operational phase as a consequence of waste thickness. Vestskoven landfill in Denmark was filled with MSWI bottom ash and fly ash between 1973 and 1976 and leachate data over 25 and 30 years respectively is presented in Environment Agency (2004a) and Hjelmar and Hansen (2004). The landfill was covered with soil only, and a LS of <1.0 has been attained over this monitoring period. This unique data set confirms the slow increase of LS in a landfill scenario, even without modern capping standards. Although the two ash waste streams are unlikely to be disposed of together in future the research at Vestskoven, nonetheless, provides a unique insight into the development of leachate chemistry with time.

Sabbas *et al.* (2003) summarise the time-scales for key geochemical processes relevant to landfilled incinerator residues. They defined 'short term' as the period within which landfill operation and active aftercare are required to meet adequate environmental protection levels. 'Long-term' represents the timeframe within which the environmental safety of the landfill no longer relies on the active protection systems, but is based on the controlled release of contaminants in an environmentally acceptable rate (Figure 14). It is clear that most geochemical processes that can influence leachate composition are likely to extend well into the aftercare period and beyond.

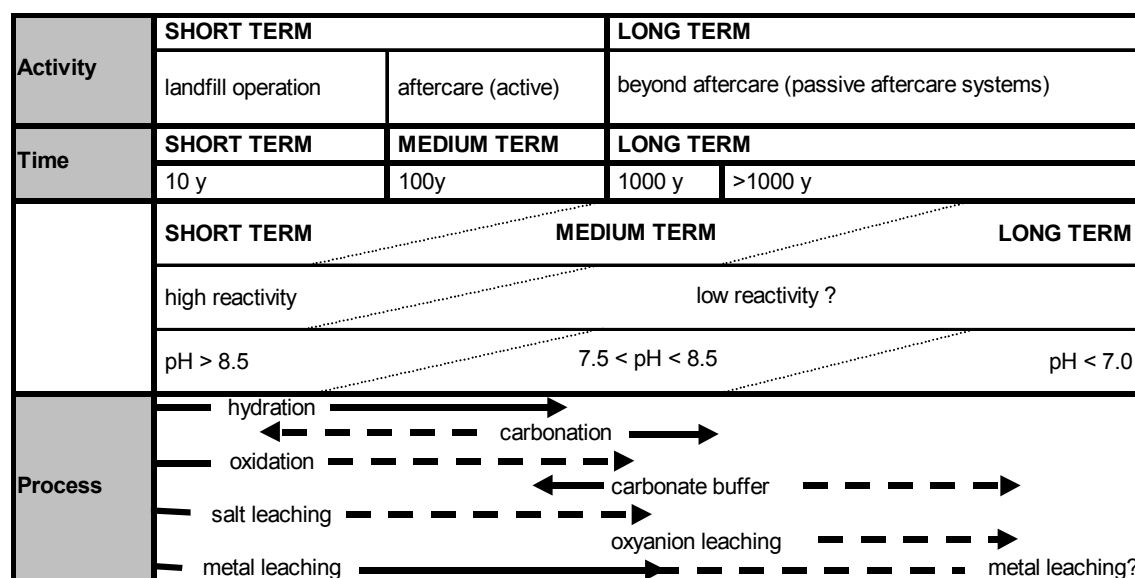


Figure 14 Classification of time scales relevant to landfilling (after Sabbas *et al.*, 2003)

Van der Sloot *et al.* (2003) compared leachate from lysimeters and field data with eluate from upflow column tests and implied, from cumulative contaminant release, that preferential flow is important and that only around 30% of the waste is involved in the leaching process.

Van Zomeren *et al.* (2003a, 2003b) report results from laboratory and field-scale leaching of cement stabilised hazardous wastes deposited at the VBM landfill, The Netherlands. To date, the leaching data shows good correlation between leached concentration and pH from field and laboratory data, and supports the identification of solubility-controlling mineral phases for heavy metals using PHREEQC (van Zomeren *et al.*, 2003a). Van der Sloot *et al.* (2003) observed good correlation between laboratory characterisation data and field leachate quality from mixed wastes, supporting the view that characterisation testing and geochemical modelling can be used effectively to predict long-term leaching behaviour.

Carbonation is an important process within both the waste and leachate collection system. Carbon dioxide uptake from the atmosphere will occur in the leachate collection and storage system reducing the pH of the leachate to near neutral (Kosson *et al.*, 1996; van Zomeren *et al.*, 2003a). This in part explains the discrepancy between high pH eluates from leach tests and circum-neutral pH of leachates from full-scale landfills.

Johnson *et al.* (1998) also observed circum-neutral pH leachate from a bottom ash landfill in Switzerland, and attributed this to carbonation along preferential flow paths indicating little interaction with the ash matrix. Occasional spikes of high pH were attributed to flushing highly alkaline porewater from the matrix during high rainfall events. The proportion of by-pass flow in the leachate reached a maximum limit of around 60%.

Valls and Vazquez (2000) and Bodénan *et al.* (2000) also considered carbonation of the waste as an important factor in determining its long-term leaching potential. Mostbauer *et al.* (2003) developed a combined weathering and upflow percolation leaching procedure and compared the results of their laboratory tests against lysimeter data. At the same liquid to solid ratio the results showed good to excellent correlation between artificially weathered inorganic waste and leachate data from the naturally-weathered waste placed in the lysimeters.

The effect of weathering on the long-term leaching, and ultimate stabilisation, of ash landfills is clearly an important area of study for both leachate source term data and prediction of time to stabilisation. Further comparative studies on the leaching performance of fresh and weathered ash are needed to better understand inorganic landfill processes and, if required, develop appropriate characterisation tests (e.g. Mostbauer *et al.*, 2003, Poletini and Pomi, 2003). Where possible, such studies should be calibrated against full-scale landfill leachate data, for example as reported by Johnson *et al.* (1998) and Hjelmar and Hansen (2004).

## 4.5 Estimated source term values

It had been hoped that a comparison of the field data obtained in Environment Agency (2004a) with the experimental data at LS 10 and LS ~1 (column test) in this study, would reveal consistent relationships. However, although the solid residues show a good correlation with other UK and European data sets, the relationships between LS 10, column tests and field leachate data were complex and inconsistent.

Possibly one of the principal contributors to this was the variation in the pH of the eluates and leachates. Field pH values appear to depend on the extent of carbonation and other ageing factors, as well as the multi-domain hydraulic characteristics of the wastes. This results in leachate composition represented by a variable mixture from carbonated and non-carbonated zones within the landfill.

However, the leaching behaviour cannot simply be attributed to pH, and inconsistent behaviour was noted both during this study and in comparing European data sets. An important example of this is Cd. Hjelmar (1996) reported Cd concentrations of up to 10-100 µg/l and 1-10 mg/l from low LS column studies on bottom ash and APC residues respectively. Hjelmar *et al.* (1999) reported average leaching of around 20 µg/l Cd based on the cumulative mass leached up to around LS 2. Leachate results from a number of landfill sites are reported in Environment Agency (2004a) and summarised for Cd below:



Lostorf *	BA	0.4 - 5.4 µg/l	pH 11.3 - 8.7
Vestskoven	85% BA 15% fly ash	< 1.0 µg/l	pH ~ 8.4 - 10.4
Site E	APC	Up to 7.3 mg/l	pH ~ 7 - 10.5

\* Johnson *et al.* (1998)

The data for Vestskoven and Site E are presented as time-series graphs (Environment Agency, 2004a) and show little correlation between Cd and pH.

Data from this study are compromised by variable reporting limits, particularly for APC residues. Most data are below reporting limits, which vary from 1 to 100 µg/l, except for the acid neutralised samples (see Section 3.4). From this, and other studies, it can be concluded that a consistent relationship for leaching of Cd cannot be made between LS 10, column tests and field data.

Despite these difficulties, some of the eluates at low LS ratio matched field data fairly well:

- Parameters such as DOC, COD, BOD, NH<sub>4</sub>-N, TKN and several of the soluble major ions were present in column eluates at roughly 5 to 10 times the LS 10 eluates and at levels similar to reported field data;
- Several metals were at similar concentrations in LS 10 and LS1 eluates, where pH was similar, suggesting equilibrium control rather than availability e.g. Zn, Pb, Mo.

Keeping in mind the caveats above, an attempt has been made to derive draft source term values from this study. These are presented below for bottom ash and APC residues, respectively. Their derivation has necessarily involved a degree of subjective judgement, and they are recommended for use not as default source term values but to inform professional judgement. They have been derived from the results in this study using a method described in Environment Agency (2004a), influenced, where appropriate, by field leachate data.

Kappa values were estimated for untreated and carbonated bottom ash and APC residues, using the comparison of leaching test results at LS 1 (column) and LS 10 (batch tests). The kappa value is derived from:

$$\text{Kappa value} = \ln [\text{LS}_1] - \ln [\text{LS 10}]/10 - 1$$

For some parameters where data are missing, kappa values have been estimated. For the acid neutralised samples, no column tests were done so the kappa values for carbonated waste have been used. It is considered that insufficient data is available for trace organics to propose source term data and site or waste stream specific data should be used on a case by case basis.

The maximum concentration, C<sub>o</sub>, has been estimated from the kappa values and C<sub>LS10</sub> from the leach tests. The spread of the data from the three incinerators provides a high end and low end estimate of the maximum value of C<sub>o</sub>. The high end estimate is taken as the maximum point of the PDF for each parameter. The low end estimate has been divided by the hydraulic factor of 5, to give the minimum point of the PDF. The most likely value still has to be evaluated, by reference to the shape of the PDF, but will usually be set closer to the maximum than the minimum.

#### 4.5.1 Bottom ash

The proposed source term data presented in Tables 17 to 19 below are derived from a limited number of laboratory tests using LS 10 batch leach tests and a recirculating upflow column test at LS 1. This information should be used to inform professional judgement when carrying out a groundwater risk assessment for a particular landfill site.

### Sources of variation

Inputs of some non-municipal waste to the incinerator (e.g. plasterboard) could affect the lime content of the ash, and hence the leachate pH and natural carbonation processes. Bottom ash from modern incinerators is likely to meet a higher standard in terms of screening and burn-out efficiency in comparison to the ash that gave rise to the leachate quality reported by Johnson *et al.* (1999) and Hjelmar and Hansen (2004). The extent of pre- and post-separation could affect the metal and

unburned organic content of the waste. The degree of burn-out (unburned organic content) and the development of biological processes within the landfill could significantly affect pH and redox potential, as well as the TOC and nitrogen content of the leachate. This, in addition to carbonation and hydrogen generation could affect metal concentrations.

The data for carbonated and acid treated bottom ash shows considerable variation in pH, and this has a significant effect on the concentrations of some contaminants, particularly amphoteric metals, in eluates.

Co-disposal with other non-hazardous wastes with low organic content may influence both the landfill processes and leachate quality and this must be taken into account when deriving leachate source term data. The hydrological setting of the landfill can also give rise to significant variation in leachate quality, due in part to the proportion of flow along preferential pathways or through the waste matrix (e.g. Johnson *et al.*, 1998).

**Table 17 Proposed contaminant range and Kappa values for untreated bottom ash**

Parameter	Units	Kappa <sup>*1</sup>	C <sub>0</sub> <sup>*2</sup>	PDF max		PDF min <sup>*3</sup>
				High	Low	
Conductivity	µS/cm	0.078	13973	17,000	8,000	1,600
TOC	mg/l	0.255	660	800	500	100
COD	mg/l	0.240	1695	2,000	1,250	250
BOD	mg/l	0.220	936	1,100	750	150
NH <sub>4</sub> -N	mg/l	0.275	16	20	15	3
TKN	mg/l	0.200	44	45		10
Na	mg/l	0.242	1208	1,300	1,000	200
K	mg/l	0.238	990	1,300	800	160
Ca	mg/l	-0.010	654	1,000	200	40
Mg	mg/l			15		3
Cl	mg/l	0.229	2131	2,700	1,800	360
SO <sub>4</sub>	mg/l	0.021	236	500	40	8
NO <sub>x</sub> -N	mg/l	-0.050	0.45	0.5	0.5	0.5
Alkalinity pH 4.5 as CaCO <sub>3</sub>	mg/l	0.051	2224	3,500	900	180
As	ug/l			1	1	0.2
Hg	ug/l	-0.426	0.00024	0.02	0.01	0.002
Cd	ug/l			1	1	0.2
Cr	ug/l	-0.100	5.2	25	7	2
Cu	ug/l	0.261	12316	17000	6000	1200
Pb	ug/l	-0.074	1892	5000	300	60
Ni	ug/l	0.173	130	180	80	16
Zn	ug/l	-0.061	588	1300	50	10
Sb	ug/l	0.060	28	30		5
Mo	ug/l	0.180	392	440	320	64
V	ug/l			5	5	5
Ba	ug/l	0.070	719	1000	400	80
Tl	ug/l			<10		
Se	ug/l			<1		
Sn	ug/l			1	1	0.2

\*1 Kappa value derived from an average of two values

\*2 derived from Kappa and LS 10 results

\*3 derived from the low PDF max divided by hydraulic factor of 5

**Table 18 Proposed contaminant range and Kappa values for carbonated bottom ash**

Parameter	Units	Kappa	C <sub>0</sub>	PDF max		PDF min
				High	Low	
Conductivity	µS/cm	0.208	14840	15000	14000	2800
TOC	mg/l	0.050	82	800	500	100
COD	mg/l	0.084	330	2000	1250	250
BOD	mg/l	-0.018	53	1100	750	150
NH <sub>4</sub> -N	mg/l	0.188	2	3	1	0
TKN	mg/l	0.256	49	50		10
Na	mg/l	0.241	1190	1700	900	180
K	mg/l	0.215	637	750	600	120
Ca	mg/l	0.157	1309	1400	1200	240
Mg	mg/l	0.358		25		5
Cl	mg/l	0.259	3217	4000	2500	500
SO <sub>4</sub>	mg/l	0.172	2794	3000	2250	450
NO <sub>x</sub> -N	mg/l	-0.146		1	1	1
Alkalinity pH 4.5 as CaCO <sub>3</sub>	mg/l	-0.082	56	200	80	15
As <sup>*1</sup>	ug/l			1	1	0.2
Hg	ug/l	0.020	0.016	0.016		0.003
Cd <sup>*2</sup>	ug/l	0.122		1.5	1	0.2
Cr	ug/l	-0.192	3	30	15	5
Cu	ug/l	0.077	944	1300	400	80
Pb	ug/l	0.172	18	30	10	2
Ni	ug/l	0.199	77	80		16
Zn	ug/l	0.200	83	90	80	16
Sb	ug/l	-0.043	52	60	45	10
Mo	ug/l	0.034	106	115	100	20
V	ug/l		16	17	15	3
Ba	ug/l	-0.041	80	120		25
Tl	ug/l					
Se	ug/l					
Sn	ug/l			1	1	0.2

\*1 maximum based on detection limit

\*2 possible underestimate of field leachate quality

**Table 19 Proposed contaminant range and Kappa values for acid treated bottom ash**

Parameter	Units	Kappa	C <sub>0</sub>	PDF max		PDF min
				High	Low	
Conductivity	µS/cm	0.208	82144	100000	60000	12000
TOC	mg/l	0.050	163	1000	500	100
COD	mg/l	0.084	842	2500	1500	300
BOD	mg/l	-0.018	102	1200	800	160
NH <sub>4</sub> -N	mg/l	0.188	13	20	6	1
TKN <sup>*1</sup>	mg/l	0.256	2723	3000	2000	400
Na	mg/l	0.241	1472	2000	1000	200
K	mg/l	0.215	821	900	700	140
Ca	mg/l	0.157	10837	3000	2000	400
Mg	mg/l	0.358	1429	2600	700	140
Cl	mg/l	0.259	3327	4500	2500	500
SO <sub>4</sub>	mg/l	0.172	3784	4400	3000	600
NO <sub>x</sub> -N <sup>*1</sup>	mg/l	-0.146	229	1200	800	160
Alkalinity pH 4.5 as CaCO <sub>3</sub>	mg/l	-0.082	48	60	30	6
As	ug/l		3.9	5	3	1
Hg	ug/l	0.020	0.08	0.16	0.03	0.01
Cd <sup>*2,3</sup>	ug/l	0.122		10	10	2
Cr	ug/l	-0.192	3.0	30	20	4
Cu	ug/l	0.077	3147	4500	1500	300
Pb	ug/l	0.172	72	110	20	4
Ni <sup>*3</sup>	ug/l	0.199		50		10
Zn <sup>*3</sup>	ug/l	0.200	114	130	100	20
Sb	ug/l	-0.043	93	160	100	20
Mo	ug/l	0.034	155	150		30
V	ug/l		46	45	10	2
Ba	ug/l	-0.041	209	300	200	40
Tl	ug/l					
Se	ug/l		10	15	6	1
Sn	ug/l			1	1	0.2

\*1 HNO<sub>3</sub> used as acid

\*2 possible underestimate of field leachate quality

\*3 BA3 excluded due to low pH

## 4.5.2 APC residues

The proposed source term data presented below is derived from a limited number of laboratory tests using LS 10 batch leach tests and a recirculating upflow column test at LS 1. For most APC residue parameters, the average C<sub>0</sub> values were very similar to the maximum values obtained from Site E data (see Section 2.5.1 of Environment Agency, 2004a). This provides some justification for the use of the kappa values derived from the experimental results. This information should be used to inform professional judgement when carrying out a groundwater risk assessment for a particular landfill site.

## Sources of variation

The eluate concentrations of some minor components (e.g. Hg, Se) varied by more than an order of magnitude for untreated APC residues, despite having very similar pH values. The causes of this kind of variation are not known but appear to be related to plant operating conditions.

A significant source of variation is the type of scrubbing process used. The values below are for residues from semi-dry scrubbing processes, the dominant type in the UK. Residues from wet-

scrubbing, a process not currently used in the UK, may contain significantly lower concentrations of Pb, Zn, Ca and Cl, and higher concentrations of SO<sub>4</sub> (Environment Agency, 2004a).

The hydrological setting of the landfill can lead to significant fluctuations of all parameters, due mainly to flow conditions within the landfill (e.g. Johnson *et al.*, 1998, 1999). It is likely that if heavy rain flushed out high pH matrix leachate from uncarbonated waste, concentrations of some metals, such as Pb and Cd could be temporarily higher than those suggested.

**Table 20 Proposed contaminant range and Kappa values for untreated APC residues**

Parameter	Units	Kappa	C <sub>0</sub>	PDF max		PDF min
				High	Low	
Conductivity	µS/cm	0.123	169910	210000	150000	30000
TOC	mg/l	0.2E	143	200	50	10
COD	mg/l	0.2E	452	600	200	40
BOD	mg/l	0.2E	79	120	20	4
NH <sub>4</sub> -N	mg/l	0.290	19	35	3	1
TKN	mg/l	0.290	97	100	4	1
Na	mg/l	0.178	8178	12000	6000	1200
K	mg/l	0.171	12067	19000	7000	1400
Ca	mg/l	0.036	12055	55000	10000	2000
Mg	mg/l	0.040		1	1	1
Cl	mg/l	0.178	94919	120000	80000	16000
SO <sub>4</sub>	mg/l	-0.036	754	1200	500	100
NO <sub>x</sub> -N	mg/l	0.2E	5	14	0	0
Alkalinity pH 4.5 as CaCO <sub>3</sub>	mg/l	-0.142	424	700	600	120
As <sup>*1</sup>	ug/l			1	1	0.2
Hg	ug/l	-0.430	0.009	1	0.001	0.0002
Cd <sup>*2</sup>	ug/l	0.05E		400	5	1
Cr <sup>*2</sup>	ug/l	0.05E		500		100
Cu	ug/l	0.058	608	1200	70	15
Pb	ug/l	-0.068	33941	600000	4000	800
Ni <sup>*2</sup>	ug/l	0.05E		150		30
Zn	ug/l	0.007	7190	3000		600
Sb <sup>*1</sup>	ug/l	0.05E		20		4
Mo	ug/l	0.019	412	600	200	40
V <sup>*1</sup>	ug/l	0.05E		100		20
Ba	ug/l	0.200	38805	44000	30000	6000
Tl <sup>*1</sup>	ug/l	0.05E		50		10
Se	ug/l	0.173	54	110	5	1
Sn <sup>*1</sup>	ug/l	0.05E		50		10

\*1 maximum value derived from reporting limit

\*2 maximum value from Site E (Environment Agency, 2004a)

E = estimated

**Table 21 Proposed contaminant range and Kappa values for carbonated APC residues**

Parameter	Units	Kappa	C <sub>0</sub>	PDF max		PDF min
				High	Low	
Conductivity	µS/cm	0.137	149325	190000	120000	25000
TOC	mg/l	0.2E		200	50	10
COD	mg/l	0.2E		600	200	40
BOD	mg/l	0.2E		120	20	4
NH <sub>4</sub> -N	mg/l	0.226	23	52	2	0.5
TKN	mg/l	0.29E		100	4	1
Na	mg/l	0.183	7395	10000	6000	1200
K	mg/l	0.179	11109	15000	7000	1400
Ca	mg/l	0.193	43924	55000	38000	7600
Mg	mg/l	0.04E		2	2	0.5
Cl	mg/l	0.175	82775	110000	67000	13000
SO <sub>4</sub>	mg/l	0.005	735	1300	300	60
NO <sub>x</sub> -N	mg/l	0.2E	3	3	0	0
Alkalinity pH 4.5 as CaCO <sub>3</sub>	mg/l		110	160	60	12
As	ug/l			1	1	0.2
Hg	ug/l	-0.406	0.011	0.03	0.002	0.0004
Cd	ug/l	0.390	629	1400	100	20
Cr	ug/l	0.05E	185	400	12	2
Cu	ug/l	0.129	307	800	40	8
Pb	ug/l	0.194	3096	8000 <sup>1</sup>	15	3
Ni	ug/l	0.05E	137	180	100	20
Zn	ug/l	0.047	253	560	30	6
Sb	ug/l	0.05E	19	165	20	4
Mo	ug/l	0.045	498	860	180	35
V	ug/l	0.05E				
Ba	ug/l	0.222	23953	31000	20000	4000
Tl	ug/l	0.05E				
Se	ug/l	0.390	147	270	65	13
Sn	ug/l	0.05E				

<sup>1</sup> High value derived from APC3 residue, pH 11.2 therefore very conservative  
E = estimated

**Table 22 Proposed contaminant range and Kappa values for acid treated APC residues**

Parameter	Units	Kappa	C <sub>0</sub>	PDF max		PDF min
				High	Low	
Conductivity	µS/cm	0.136	306602	320000	290000	60000
TOC	mg/l	0.2E	94	175	50	10
COD	mg/l	0.2E	307	400	200	40
BOD	mg/l	0.2E	49	50		10
NH <sub>4</sub> -N	mg/l	0.226	17	40	4	1
TKN	mg/l	0.290				
Na	mg/l	0.183	8926	11300	7500	1500
K	mg/l	0.179	13000	17000	8000	1600
Ca	mg/l	0.193	146000	160000	125000	25000
Mg	mg/l	0.04E	47	100	20	4
Cl	mg/l	0.175	83354	110000	60000	12000
SO <sub>4</sub>	mg/l	0.005	1314	1500	1200	240
NO <sub>x</sub> -N <sup>*1</sup>	mg/l	0.2E	4295	12000	130	26
Alkalinity pH 4.5 as CaCO <sub>3</sub>	mg/l			76	38	8
As	ug/l		8	12	6	1
Hg	ug/l	-0.406		0.034	0.001	0.0002
Cd	ug/l	0.390	4015	10000	750	150
Cr	ug/l	0.05E	65	100	25	5
Cu	ug/l	0.129	385	650	125	25
Pb	ug/l	0.194	152474	275000 <sup>*1</sup>	30000	6000
Ni	ug/l	0.05E	380	400	350	70
Zn	ug/l	0.047	1214	2400	600	120
Sb	ug/l	0.05E	253	1000	200	40
Mo	ug/l	0.045	896	1200	500	100
V	ug/l	0.05E				
Ba	ug/l	0.222	50426	60000	44000	9000
Tl	ug/l	0.05E				
Se	ug/l	0.390	2880	7600	400	80
Sn	ug/l	0.05E				

\*1 Influenced by one APC1 replicate

E = estimated

## 4.6 Conclusions

Incinerator residue arisings in the UK are mainly disposed of to landfill; around 80% of the 0.6 Mt of bottom ash and 88% of the 80,000 t of APC residues at current production rate (Environment Agency, 2002). Some 50% of the APC residues are deposited at a single ash landfill and the remainder to co-disposal landfills. The UK will need to find alternative strategies to manage incineration residues due to the ban on co-disposal of hazardous and non-hazardous wastes, pressure to recover an increasing proportion of bottom ash, and an anticipated need for increased incineration capacity.

There is a considerable body of data on MSW incinerator residues in Europe and beyond (e.g. Hjelmar, 1996, IAWG, 1997) and general conclusions can be made on the chemistry of ash streams. However, although some general relationships can be drawn between laboratory eluate and field leachate data there are a number of inconsistencies, most significantly for Cd, both from this project and when data is compared with other sources. There is also little information available on the nature of DOC or speciation of trace organics present in residues.

Two treatment methods, accelerated carbonation and acid neutralisation, were carried out to assess their impact on eluate chemistry. This report concludes that the hazardous properties of incinerator

residues can be reduced by carbonation due to consumption of lime and precipitation of calcite. This results in a pH reduction, although not by as much as expected under the conditions of this study. However, other researchers have achieved consistent results below pH 9.

Heavy metal concentrations in eluates can also be significantly reduced, in particular Pb and Zn, Ba (bottom ash), Cu and Se (both APC). However, further work is required to evaluate the effect of carbonation on leaching Cd from APC residues. Notwithstanding this, carbonation shows promise as a treatment technology as pH reduction is achieved without significant loss of acid buffering capacity.

Acid neutralisation yielded far more variable replicate data than both the untreated and carbonated eluates. Heavy metal concentrations were also significantly reduced, particularly Pb and Zn. However, some metals were released in significant concentrations, in particular Cd, Sb and Mo. Cu concentrations in bottom ash eluates were also elevated, possibly due to complexation with DOC released from bottom ash samples.

Leachate source term data is proposed, primarily from the results of this study and supplemented by field data. It was beyond the scope of this study to compile source term data from the wealth of published literature available, but comparisons were made with other data sets as a quality check on the data from this study. This information should be used to inform professional judgement when carrying out a groundwater risk assessment for a particular landfill site that contains a significant proportion of incinerator residues.

The management of leachate from landfill sites containing predominantly incinerator residues cannot be considered in isolation from other landfill processes, including the likelihood and longevity of biodegradation (e.g. of unburned paper), the implication of changing redox conditions, the generation of gases (e.g. from methanogenesis and elemental metal corrosion), temperature development, landfill hydraulics, the efficacy of leachate collection systems, and the effect of long-term changes (e.g. carbonation, humification) on the release of contaminants. Sabbas *et al.* (2003) present an excellent overview of management of incineration residues, and a number of research areas can be highlighted.

Key research needs are summarised below:

- Evaluation of the chemistry and mineralogy of residues; in particular the origin and composition of DOC and its impact on mobilisation of metals and trace organics (e.g. Kim and Osako, 2004, Zhang *et al.*, 2004);
- Evaluate the potential for gas (e.g. Magel *et al.*, 2001) and heat (e.g. Huber, 1998) evolution, their influence on landfill processes and conditions, and liner integrity;
- Evaluate the influence of weathering on the leaching performance of residues (e.g. Bodénan *et al.*, 2000, Polettini and Pomi, 2003, Mostbauer *et al.*, 2003);
- Evaluation of the influence of dissolution and carbonation on the mechanical properties of residues, treated residues and the stability of incinerator residue landfills;
- Evaluation and compilation of leachate quality data from landfill sites containing predominantly MSWI residues;
- Measurement and modelling of landfill hydraulics; and
- Evaluation of treatment technologies to enable re-use of residues, compliance with the WACs, and/or reduce the time to reach equilibrium status (Hall *et al.*, 2004).



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# Appendix A: Details of sampling of MSWI residues

**MSW INCINERATOR RESIDUES TESTING: PRIMARY SAMPLING LOG for Site 1 (page 1 of 2)**

Plant	Date	Material Type	Source	Bin no.	Time Sampled	Weights (kg)			Sampler	Comments
						Empty Bin	Filled	Ash		
Site 1	27.5.02	BA <12mm	Mix of Lines 1 & 2	KK1	10:00				KK/RWF	bulk density ~2kg/l
Site 1	27.5.02	BA <12mm	Mix of Lines 1 & 2	KK2	10:00				KK/RWF	bulk density ~2kg/l
Site 1	27.5.02	BA <12mm	Mix of Lines 1 & 2	KK3	10:00				KK/RWF	bulk density ~2kg/l
Site 1	27.5.02	BA <12mm	Mix of Lines 1 & 2	KK4	10:00			180 kg	KK/RWF	bulk density ~2kg/l
Site 1	27.5.02	BA <12mm	Mix of Lines 1 & 2	KK5	10:00				KK/RWF	bulk density ~2kg/l
Site 1	27.5.02	BA <12mm	Mix of Lines 1 & 2	KK6	10:00				KK/RWF	bulk density ~2kg/l
Site 1	27.5.02	BA +12	Mix of Lines 1 & 2	KK7	10:00				KK/RWF	discarded after weighing
Site 1	27.5.02	BA +12	Mix of Lines 1 & 2	KK8	10:00			100 kg	KK/RWF	discarded after weighing
Site 1	27.5.02	BA +12	Mix of Lines 1 & 2	KK9	10:00				KK/RWF	discarded after weighing
Site 1	27.5.02	BA +12	Mix of Lines 1 & 2	KK10	10:00				KK/RWF	discarded after weighing
		BA <12mm = bottom ash material passing a 12 mm sieve BA +12 = bottom ash material retained on a 12mm sieve.						Total BA 280 kg <12mm = 180/280 = 64% ∴ rejects = 100/280 = 36%		

**MSW INCINERATOR RESIDUES TESTING: PRIMARY SAMPLING LOG for Site 1 (page 2 of 2)**

Plant	Date	Material Type	Source	Bin no.	Time Sampled	Weights (kg)			Sampler	Comments
						Empty Bin	Filled	Ash		
Site 1	27.5.02	APC/fly ash	Mix of Lines 1 and 2	KK11	25 <sup>th</sup> and 26 <sup>th</sup> May 2002			} 60 kg	Operator	
Site 1	27.5.02	APC/fly ash	Mix of Lines 1 and 2	KK12	25 <sup>th</sup> and 26 <sup>th</sup> May 2002				Operator	
Site 1	27.5.02	APC/fly ash	Mix of Lines 1 and 2	KK13	25 <sup>th</sup> and 26 <sup>th</sup> May 2002				Operator	
Site 1	27.5.02	APC/fly ash	Mix of Lines 1 and 2	KK14	25 <sup>th</sup> and 26 <sup>th</sup> May 2002				Operator	

APC material was collected in six bins, three per Line, by the Operator, over two days. We then mixed and homogenised the whole set on site, using coning and quartering.

60 kg occupied four bins to a volume of ~20 litres each, giving a bulk density of ~0.75 kg/l.

**MSW INCINERATOR RESIDUES TESTING: PRIMARY SAMPLING LOG for Site 2 (page 1 of 1)**

Plant	Date	Material Type	Source	Bin no.	Time Sampled	Weights (kg)			Sampler	Comments
						Empty Bin	Filled	Ash		
Site 2	20.6.02	BA <12mm	Stockpile	KK15	11:50		39.0	} 117.5	RWF	25kg of this bin sent for carbonation
Site 2	20.6.02	BA <12mm	Stockpile	KK16	11:50		38.5		RWF	
Site 2	20.6.02	BA <12mm	Stockpile	KK17	11:50		40.0		RWF	
Site 2	20.6.02	BA +12	Stockpile	KK7	12:00		21.0	} 58.5	RWF	discarded after weighing
Site 2	20.6.02	BA +12	Stockpile	KK8	12:00		16.5		RWF	discarded after weighing
Site 2	20.6.02	BA +12	Stockpile	KK9	12:00		21.0		RWF	discarded after weighing
		BA <12mm = bottom ash material passing a 12 mm sieve BA +12 = bottom ash material retained on a 12mm sieve.						Total BA 176 kg <12mm = 117.5/176 = 67% ∴ rejects = 58.5/176 = 33%		
Site 2	20.6.02	APC/fly ash	Silos	KK18	12:20-12:40			} 31 kg	Operator	sampled in our presence
Site 2	20.6.02	APC/fly ash	Silos	KK19	12:20-12:40				Operator	sampled in our presence
		APC/fly ash residues were collected from two silos on site, and mixed subsequently at our laboratory by coning and quartering.								



**MSW INCINERATOR RESIDUES TESTING: PRIMARY SAMPLING LOG for Site 3 (page 1 of 1)**

Plant	Date	Material Type	Source	Bin no.	Time Sampled	Weights (kg)			Sampler	Comments
						Empty Bin	Filled	Ash		
Site 3	24.6.02	BA <12mm	Stockpile	KK21	09:45		22.5	} 108.0	KK/RWF	
Site 3	24.6.02	BA <12mm	Stockpile	KK22	09:45		21.0		KK/RWF	this bin sent for carbonation
Site 3	24.6.02	BA <12mm	Stockpile	KK23	09:45		22.5		KK/RWF	
Site 3	24.6.02	BA <12mm	Stockpile	spare for discard	09:45		25.5		KK/RWF	
Site 3	24.6.02	BA <12mm	Stockpile	spare for discard	09:45		16.5		KK/RWF	
Site 3	24.6.02	BA +12	Stockpile	1	09:45		24.0	} 84.5	KK/RWF	discarded after weighing
Site 3	24.6.02	BA +12	Stockpile	2	09:45		24.5		KK/RWF	discarded after weighing
Site 3	24.6.02	BA +12	Stockpile	3	09:45		21.5		KK/RWF	discarded after weighing
Site 3	24.6.02	BA +12	Stockpile	4	09:45		14.5		KK/RWF	discarded after weighing
								Total BA 192.5 kg <12mm = 108/192.5 = 56% ∴ rejects = 84.5/192.5 = 44%		
Site 3	22.6.02	APC/fly ash	Silo	"Saturday bag"			18.5	} 35.0	operator	collected at hourly intervals over 24 hours
Site 3	23.6.02	APC/fly ash	Silo	"Sunday bag"			16.5		operator	collected at hourly intervals over 24 hours
								The two bags of APC/fly ash residue were combined and mixed at our laboratory		

# Appendix B: Report by Lafarge Envirocem on the carbonation of samples

## Introduction

An Environment Agency project is underway to look at the carbonation of municipal solid waste incineration (MSWI) ashes from three incinerators in the UK. Samples of bottom ash (normally a coarse clinker) and fly ash/APC residues (fine powder) were provided for carbonation by exposure to a 100% carbon dioxide atmosphere for 20 minutes.

## Carbonation chamber

The carbonation chamber, which was based at Lafarge Envirocem Solutions (near Nottingham), consists of a horizontally mounted cylindrical drum fitted with a paddle blade along the central axis. The dimensions of the drum are as follows: 500 mm diameter x 700 mm length and an internal volume of 140 litres, although the recommended working capacity is 80 litres. A 5.5 horsepower motor drives the paddle blades. The chamber is fitted with a hinged access hatch and a hand operated "bomb" door outlet. Gaseous carbon dioxide is fed into the chamber from a liquid CO<sub>2</sub> cylinder via a vaporisation unit, which consists of a series of metal tubes, so that ambient temperature converts the liquid into gas. Exhaust gases are removed via a carbon filter to the atmosphere.

## Methodology

Previous work relating to the carbonation of wastes had indicated that too much water might impede carbonation and, therefore, the bottom ashes were dried at 50°C (to avoid loss of organic compounds) for 3 days prior to treatment. Similar work with fine powders had also indicated that a certain amount of water was necessary to allow carbonation to proceed, the optimum being about 20% for most materials. The APC residues were, therefore, mixed with 20% water in the carbonation chamber for 10 minutes prior to introduction of gaseous carbon dioxide. The mixer was operated during the carbonation time of 20 minutes, to break up any agglomerates and to continually expose fresh surfaces to the gas. On completion of treatment, the material was placed into a plastic drum and sealed. Treated samples were sent to Enviro Consulting Ltd for leach testing.

Moisture contents were obtained on receipt of the sample and before and after treatment (except for RWF1 and RWF2) and the data is recorded in Tables 1 (bottom ash) and 2 (APC residues). The bottom ashes showed little moisture loss during treatment whilst the AP residues lost significant quantities (about 50%); probably associated with the high temperatures generated (see Table 4). The accelerated carbonation reaction is usually characterised by a rapid rise in temperature and it is evident that the APC residues responded better to carbonation than the bottom ashes (Table 3).

**Table 1 Physical properties of the bottom ashes.**

Sample	Appearance	Moisture content, as received (%)	Moisture content before treatment (%)	Moisture content after treatment (%)
RWF2	Coarse grey clinker	18.7	14.1	N/K
KK15	Coarse black clinker	35.4	18.4	15.9
KK22	Similar to KK22	18.5	13.1	13.1

**Table 2 Physical properties of the APC residues**

Sample	Density (kg/m <sup>3</sup> )	Moisture content, as received (%)	Moisture content before treatment (%)	Moisture content after treatment (%)
RWF1	570	0	20	N/K
KK19	619	0	20	9.7
RWF3	735	0	20	9.7

**Table 3 Observations during treatment of the bottom ashes**

Sample	Temperature before treatment (°C)	Temperature after treatment (°C)	Appearance after treatment
RWF2	15	28	Wet putty
KK15	19	24	Coarse clinker
KK22	20	31	Coarse clinker

**Table 4 Observations during treatment of the APC residues**

Sample	Temperature before treatment (°C)	Temperature after addition of water (°C)	Temperature after treatment (°C)	Appearance
RWF1	18	35	68	Coarse grey powder
KK19	19	35	70	Dark grey sticky powder
RWF3	20	42	75	Similar to treated KK19

# Appendix C: Details of LS 10 leaching tests

### Site 1 eluate testing of MSWI residues at LS 10

Waste type	Replicate number	Source Bin label	Weight used (g)	Leachant volume (ml)	Date & time solids weighed	Date & time leachant added	Date & time roller started	Date & time roller stopped	Date & time filtered	Date & time eluates split	Date sent to EA lab
APC	1	14	90.2	900	17/6 11.05	17/6 11.05	17/6 12.10	not recorded	18/6 11.05	not recorded	27/6/02
APC	2	14	90.4	900	17/6 11.10	17/6 11.10	17/6 12.10		18/6 11.15		
APC	3	14	90.1	900	17/6 11.15	17/6 11.15	17/6 12.10		18/6 11.25		
APC	4	14	90.1	900	17/6 11.20	17/6 11.20	17/6 12.10		18/6 11.35		
APC	5	12	90.0	900	17/6 11.25	17/6 11.25	17/6 12.10		18/6 11.45		
blank		-	-	900	17/6 11.00	17/6 11.00	17/6 12.10		18/6 10.55		
T-APC	1	RWF-1	108.3	900	17/6 11.35	17/6 11.35	17/6 12.10	not recorded	18/6 12.00	not recorded	27/6/02
T-APC	2	RWF-1	107.8	900	17/6 11.45	17/6 11.45	17/6 12.10		18/6 12.15		
T-APC	3	RWF-1	107.9	900	17/6 11.50	17/6 11.50	17/6 12.10				
T-APC	4	RWF-1	108.2	900	17/6 12.00	17/6 12.00	17/6 12.10				
T-APC	5	RWF-1	108.1	900	17/6 12.10	17/6 12.10	17/6 12.10				
BA	1	KK1	111.2	880	17.6.02	18/6 10.00	18/6 10.25	not recorded	not recorded	not recorded	27/6/02
BA	2	KK2	111.4	880	17.6.02	18/6 10.00	18/6 10.25				
BA	3	KK3	111.5	880	17.6.02	18/6 10.00	18/6 10.25				
BA	4	KK4	111.3	880	17.6.02	18/6 10.00	18/6 10.25				
BA	5	KK6	111.3	880	17.6.02	18/6 10.00	18/6 10.25				
blank		-	-	880	-	18/6 10.00	18/6 10.25				
T-BA	1	RWF-2	104.5	885	17.6.02	18/6 10.00	18/6 10.25	not recorded	not recorded	not recorded	27/6/02
T-BA	2	RWF-2	104.3	885	17.6.02	18/6 10.00	18/6 10.25				
T-BA	3	RWF-2	104.6	885	17.6.02	18/6 10.00	18/6 10.25				
T-BA	4	RWF-2	104.6	885	17.6.02	18/6 10.00	18/6 10.25				
T-BA	5	RWF-2	108.0	885	17.6.02	18/6 10.00	18/6 10.25				

### Site 2 eluate testing of MSWI residues at LS 10

Waste type	Replicate number	Source Bin label	Weight used (g)	Leachant volume (ml)	Date & time solids weighed	Date & time leachant added	Date & time roller started	Date & time roller stopped	Date & time filtered	date & time eluates split	date sent to EA lab
APC	1	Mix	90.3	900	8/7 14:00	8/7 14:01	8/7 14:37	not recorded	not recorded	10/7/02	16/7/02
APC	2		89.9	900	8/7 14:07	8/7 14:08				14:00-14:55	
APC	3		90.2	900	8/7 14:14	8/7 14:15					
APC	4		89.8	900	8/7 14:21	8/7 14:22					
APC	5		90.3	900	8/7 14:28	8/7 14:29					
blank x 2				900 x 2		8/7 14:36					
T-APC	1	KK19	99.6	890	10/7 13:18	10/7 13:19	10/7 13:42	11/7 13:04	11/7 14:07	11/7 14:08	
T-APC	2		99.8	890	10/7 13:23	10/7 13:24			11/7 14:21	11/7 14:22	
T-APC	3		99.8	890	10/7 13:29	10/7 13:30			11/7 14:37	11/7 14:38	
T-APC	4		99.7	890	10/7 13:34	10/7 13:35			11/7 14:53	11/7 14:54	
T-APC	5		99.6	890	10/7 13:39	10/7 13:40			11/7 15:06	11/7 15:07	
BA	1	KK17	139.1	851	8/7 13:25	8/7 13:26	8/7 14:37	not recorded	not recorded	10/7/02	16/7/02
BA	2		139.3	851	8/7 13:32	8/7 13:33				14:55-15:45	
BA	3		139.6	851	8/7 13:39	8/7 13:40					
BA	4		139.2	851	8/7 13:46	8/7 13:47					
BA	5		139.3	851	8/7 13:53	8/7 13:54					
blank x 2				900 x 2		10/7 12:00			11/7 13:25	11/7 13:26	
TBA	1	KK15	107.3	883	10/7 12:14	10/7 12:15	10/7 13:42	11/7 13:04	11/7 16:27	11/7 16:28	
TBA	2		107.4	883	10/7 12:20	10/7 12:21			11/7 16:19	11/7 16:20	
TBA	3		107.1	883	10/7 12:27	10/7 12:28			11/7 15:40	11/7 15:41	
TBA	4		107.3	883	10/7 12:31	10/7 12:32			11/7 15:55	11/7 15:56	
TBA	5		107.1	883	10/7 12:36	10/7 12:37			11/7 16:07	11/7 16:08	

### Site 3 eluate testing of MSWI residues at LS 10

Waste type	Replicate number	Source Bin label	Weight used (g)	Leachant volume (ml)	Date & time solids weighed	Date & time leachant added	date & time roller started	date & time roller stopped	date & time filtered	date & time eluates split	date sent to EA lab			
APC	1		90.0	900	16/7 11:40	16/7 11:42	16/7/02 12:28	17/7/02 13:34	18/7 13:45	18/7	19/7/02			
APC	2		90.0	900	16/7 12:00	16/7 12:01			18/7 10:40	18/7 10:48				
APC	3		90.0	900	16/7 11:54	16/7 11:56			18/7 12:25	18/7 12:30				
APC	4		90.0	900	16/7 11:48	16/7 11:50			18/7 13:33	18/7 13:39				
APC	5		90.1	900	16/7 11:34	16/7 11:37			18/7 13:20	18/7 13:27				
blank x 2				900 x 2	16/7 11:40	16/7 11:25			17/7 14:06	17/7 14:19				
									18/7 14:45	18/7 14:51				
T-APC	1		99.8	890	16/7 12:25	16/7 12:28			18/7 14:33	18/7 14:39				
T-APC	2		99.8	890	16/7 12:10	16/7 12:12			18/7 14:06	18/7 14:14				
T-APC	3		99.7	890	16/7 12:20	16/7 12:22			18/7 14:20	18/7 14:26				
T-APC	4		99.7	890	16/7 12:16	16/7 12:18			18/7 14:56	18/7 15:05				
T-APC	5		99.6	890	16/7 12:05	16/7 12:06								
BA	1	KK23	110.4	880	not recorded	15/7 10:37			15/7/02 11:41	16/7/02 11:17		17/7 15:17	17/7 15:23	19/7/02
BA	2		110.2	880		15/7 10:29						17/7 14:36	17/7 14:45	
BA	3		110.4	880		15/7 10:51						17/7 15:05	17/7 15:11	
BA	4		110.6	880		15/7 10:44	17/7 14:52	17/7 14:58						
BA	5		110.4	880		15/7 10:57	17/7 14:24	17/7 14:33						
blank x 2						900 x 2	15/7 10:21	17/7 15:43			17/7 15:50			
TBA	1			103.5		886	15/7 11:41	17/7 17:11			17/7 17:16			
TBA	2			103.5		886	15/7 11:34	17/7 16:58			17/7 17:04			
TBA	3			103.4		886	15/7 11:29	17/7 16:27			17/7 16:32			
TBA	4			103.4		886	15/7 11:24	17/7 16:00			17/7 16:05			
TBA	5			103.6		886	15/7 11:18	17/7 16:16			17/7 16:21			



# Appendix D: Details of acid leaching tests at LS 10

### Site 1 acid leaching test at LS 10

Waste type	Replicate number	Source Bin label	Weight used (g) for three levels of acid addition	Leachant volume (ml)	Ratio of 2M HNO <sub>3</sub> : water in leachant			Date & time roller started	Date filtered	Results of pH checks on random replicates	Date sent to EA lab
					Low acid	Medium	High acid				
			low/medium/high		Low acid	Medium	High acid				
BA	1	KK2	111.1/111.8/ <b>111.4</b>	880	37:843	40:840	<b>43:837</b>	11/9/02	12/9/02	Rep1 L 10.25	12/9/02
BA	2	KK2	111.3/110.6/ <b>111.5</b>	880	37:843	40:840	<b>43:837</b>	14:07			
BA	3	KK2	111.1/111.4/111.5	880	37:843	40:840	43:837			Rep3 H 9.15	
BA	4	KK2	110.9/111.2/ <b>111.1</b>	880	37:843	40:840	<b>43:837</b>			Rep4 M 9.95	
BA	5	KK2	111.5/111.2/ <b>111.6</b>	880	37:843	40:840	<b>43:837</b>				
APC	1	KK 11	90.4/ <b>89.6</b> /90.0	900	235:665	<b>250:650</b>	265:635	2/10/02	3/10/02		11/10/02
APC	2	KK 11	90.2/ <b>90.4</b> /90.1	900	235:665	<b>250:650</b>	265:635	16:11		Rep2 L 10.15	
APC	3	KK 11	90.1/ <b>89.7</b> /90.2	900	235:665	<b>250:650</b>	265:635				
APC	4	KK 11	90.1/89.9/89.9	900	235:665	250:650	265:635			Rep4 M 8.15	
APC	5	KK 11	90.2/ <b>90.3</b> /90.1	900	235:665	<b>250:650</b>	265:635			Rep4 H 7.4	

Note: pH checked on one replicate chosen at random from each level of acid addition; the set with pH nearest to 8.3 were chosen for analysis, the remainder being discarded. The four replicates sent for analysis are shown in **bold italic**.

## Site 2 acid leaching test at LS 10

Waste type	Replicate number	Source Bin label	Weight used (g) for three levels of acid addition	Leachant volume (ml)	Ratio of 2M HNO <sub>3</sub> : water in leachant			Date & time roller started	Date filtered	Results of pH checks on random replicates	Date sent to EA lab
					Low acid	Medium	High acid				
			low/medium/high		Low acid	Medium	High acid				
BA	1	KK 16	<b>139.4</b> /139.3/139.6	851	<b>27/824</b>	29/822	31/820	9/9/02	10/9/02		12/9/02
BA	2	KK 16	139.6/139.1/139.8	851	27/824	29/822	31/820	13:07		Rep2 L 8.2	
BA	3	KK 16	<b>139.0</b> /138.8/139.0	851	<b>27/824</b>	29/822	31/820			Rep3 M 7.95	
BA	4	KK 16	<b>139.1</b> /139.4/139.8	851	<b>27/824</b>	29/822	31/820			Rep4 H 7.65	
BA	5	KK 16	<b>138.7</b> /139.6/139.2	851	<b>27/824</b>	29/822	31/820				
APC	1	Mix	90.2/ <b>90.1</b> /90.2	900	350/550	<b>400/500</b>	450/450	7/10/02	8/10/02		11/10/02
APC	2		90.4/ <b>89.9</b> /89.8	900	350/550	<b>400/500</b>	450/450	12:46			
APC	3		90.3/ <b>90.2</b> /89.7	900	350/550	<b>400/500</b>	450/450			Rep5 L 11.15	
APC	4		89.9/ <b>90.0</b> /90.0	900	350/550	<b>400/500</b>	450/450			Rep5 M 8.40	
APC	5		90.0/90.2/90.2	900	350/550	400/500	450/450			Rep5 H 4.55	

Note: pH checked on one replicate chosen at random from each level of acid addition; the set with pH nearest to 8.3 were chosen for analysis, the remainder being discarded. The four replicates sent for analysis are shown in **bold italic**.

### Site 3 acid leaching test at L/S 10

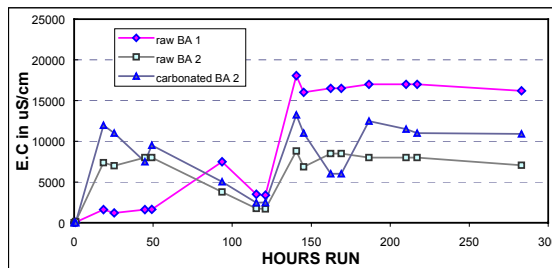
Waste type	Replicate number	Source Bin label	Weight used (g) for three levels of acid addition	Leachant volume (ml)	Ratio of 2M HNO <sub>3</sub> : water in leachant			Date & time roller started	Date filtered	Results of pH checks on random replicates	Date sent to EA lab
					Low acid	Medium	High acid				
			low/medium/high		Low acid	Medium	High acid				
BA	1	KK 21	<b>110.3</b> /109.9/110.9	880	<b>55/825</b>	60/820	65/815	1/10/02	3/10/02	Rep3 H 6.00 Rep4 L 6.55 Rep4 M 6.15	11/10/02
BA	2	KK 21	<b>110.1</b> /110.5/110.8	880	<b>55/825</b>	60/820	65/815	12:58			
BA	3	KK 21	<b>110.4</b> /110.0/109.9	880	<b>55/825</b>	60/820	65/815				
BA	4	KK 21	110.2/110.4/110.8	880	55/825	60/820	65/815				
BA	5	KK 21	<b>110.8</b> /110.4/110.2	880	<b>55/825</b>	60/820	65/815				
APC	1	KK24a	89.8/ <b>90.1</b> /90.1	900	320/580	<b>350/550</b>	380/520	8/10/02	10/10/02	Rep3 L 10.3 Rep4 M 7.70 Rep4 H 5.05	11/10/02
APC	2	KK24a	90.1/ <b>89.9</b> /90.0	900	320/580	<b>350/550</b>	380/520	15:11			
APC	3	KK24a	90.0/ <b>90.1</b> /90.3	900	320/580	<b>350/550</b>	380/520				
APC	4	KK24a	90.1/90.2/90.1	900	320/580	350/550	380/520				
APC	5	KK24a	90.1/ <b>90.0</b> /90.0	900	320/580	<b>350/550</b>	380/520				

Note: pH checked on one replicate chosen at random from each level of acid addition; the set with pH nearest to 8.3 were chosen for analysis, the remainder being discarded. The four replicates sent for analysis are shown in **bold italic**.

# Appendix E: Stage 3 column tests - conductivity results and graphs

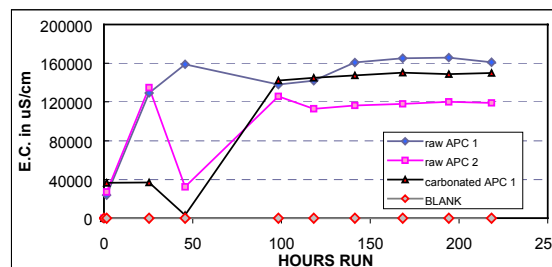
Date time	HOURS		carbonated			Notes
	RUN	raw BA 1	raw BA 2	BA 2	BA 2	
		$\mu\text{S/cm}$	$\mu\text{S/cm}$	$\mu\text{S/cm}$	$\mu\text{S/cm}$	
23/10/02 14:40	0	5	5	5	5	Just before first drops flowed
23/10/02 15:40	1	62	142	7	7	
24/10/02 09:15	19	1,607	7,390	11,980		
24/10/02 16:00	25	1,200	7,000	11,000		
25/10/02 11:30	45	1,600	8,000	7,500		
25/10/02 15:45	49	1,650	8,000	9,500		
27/10/02 12:13	94	7,500	3,780	5,020		Electricity off from 10.30 to 16.30
28/10/02 10:00	115	3,500	1,750	2,450		
28/10/02 15:40	121	3,400	1,700	2,500		
29/10/02 11:20	141	18,070	8,790	13,260		
29/10/02 16:00	145	16,000	6,850	11,000		
30/10/02 09:00	162	16,500	8,500	6,000		
30/10/02 15:45	169	16,500	8,500	6,000		
31/10/02 09:15	187	17,000	8,000	12,500		
01/11/02 08:45	210	17,000	8,000	11,500		
01/11/02 15:45	217	17,000	8,000	11,000		
04/11/02 09:50	283	16,200	7,050	10,900		

Circulation stopped at ~10:30 and columns allowed to drain



Date	HOURS		carbonated			Notes
	RUN	raw APC 1	raw APC 2	APC 1	BLANK	
		$\mu\text{S/cm}$	$\mu\text{S/cm}$	$\mu\text{S/cm}$	$\mu\text{S/cm}$	
06/11/02 13:00	0	9	10	9	10	All started
06/11/02 13:30	0.50					
06/11/02 14:30	1.50	23,800	27,200	36,600	24	
07/11/02 14:30	25.50	129,300	134,700	37,000	38	
08/11/02 10:45	45.75	159,000	32,400	3,280	20	l-litre water added APC2 & TAPC1
10/11/02 15:15	98.25	138,000	125,800	142,200	37	l-litre water added APC2
11/11/02 11:10	118.17	142,000	113,000	145,000	37	
12/11/02 10:20	141.33	160,800	116,500	147,400	37	
13/11/02 13:20	168.33	165,200	118,000	150,100	37	
14/11/02 15:15	194.25	165,900	120,000	148,900	37	
15/11/02 15:15	218.25	161,000	119,000	150,000	37	

Circulation stopped at ~15:30.  
Columns left standing over weekend, not draining.



# Appendix F: Log of laboratory analysis of solids and eluates

Sample	Test	Date to lab	Date results received		
			basic	List 1	dioxin
BA1	Stage 1 solids analysis	27.6.02	6.9-21.11.02	20.9.02	12.2.03
t-BA1	Stage 1 solids analysis	27.6.02	6.9-21.11.02	20.9.02	12.2.03
BA2	Stage 1 solids analysis	16.7.02	20.11.02	20.9.02	12.2.03
t-BA2	Stage 1 solids analysis	16.7.02	20.11.02	20.9.02	12.2.03
BA3	Stage 1 solids analysis	19.7.02	2.12.02	20.9.02	12.2.03
t-BA3	Stage 1 solids analysis	19.7.02	2.12.02	20.9.02	12.2.03
APC1	Stage 1 solids analysis	27.6.02	6.9-21.11.02	20.9.02	12.2.03
t-APC1	Stage 1 solids analysis	27.6.02	6.9-21.11.02	20.9.02	12.2.03
APC2	Stage 1 solids analysis	16.7.02	20.11.02	20.9.02	12.2.03
t-APC2	Stage 1 solids analysis	16.7.02	20.11.02	20.9.02	12.2.03
APC3	Stage 1 solids analysis	19.7.02	? 2.12.02	20.9.02	12.2.03
t-APC3	Stage 1 solids analysis	19.7.02	? 2.12.02	20.9.02	12.2.03
BA1	Stage 2 eluates	27.6.02	21.11.02	20.9.02	21.11.02
t-BA1	Stage 2 eluates	27.6.02	21.11.02	20.9.02	21.11.02
BA2	Stage 2 eluates	16.7.02	20.11.02	20.9.02	20.11.02
t-BA2	Stage 2 eluates	16.7.02	20.11.02	20.9.02	20.11.02
BA3	Stage 2 eluates	19.7.02	2.12.02	20.9.02	2.12.02
t-BA3	Stage 2 eluates	19.7.02	2.12.02	20.9.02	2.12.02
APC1	Stage 2 eluates	27.6.02	21.11.02	20.9.02	21.11.02
t-APC1	Stage 2 eluates	27.6.02	21.11.02	20.9.02	21.11.02
APC2	Stage 2 eluates	16.7.02	20.11.02	20.9.02	20.11.02
t-APC2	Stage 2 eluates	16.7.02	20.11.02	20.9.02	20.11.02
APC3	Stage 2 eluates	19.7.02	2.12.02	20.9.02	2.12.02
t-APC3	Stage 2 eluates	19.7.02	2.12.02	20.9.02	2.12.02
Blanks	Stage 2 eluates	27.6.02	21.11.02	20.9.02	21.11.02
Blanks	Stage 2 eluates	16.7.02	20.11.02	20.9.02	20.11.02
Blanks	Stage 2 eluates	19.7.02	2.12.02	20.9.02	2.12.02
BA1	Stage 2 acid leach test	12.9.02	15.01.03	4.12.02	15.01.03
BA2	Stage 2 acid leach test	12.9.02	15.01.03	4.12.02	15.01.03
BA3	Stage 2 acid leach test	11.10.02	15.01.03	4.12.02	15.01.03
APC1	Stage 2 acid leach test	11.10.02	15.01.03	4.12.02	15.01.03
APC2	Stage 2 acid leach test	11.10.02	15.01.03	4.12.02	15.01.03
APC3	Stage 2 acid leach test	11.10.02	15.01.03	4.12.02	15.01.03
blanks	Stage 2 acid leach test	12.9 & 11.10.02	15.01.03		
BA1	Stage 3 column leachate	7.11.02	15.01.03	5.12.02	15.01.03
BA2	Stage 3 column leachate	7.11.02	15.01.03	5.12.02	15.01.03
t-BA2	Stage 3 column leachate	7.11.02	15.01.03	5.12.02	15.01.03
APC1	Stage 3 column leachate	18.11.02	17.1.03	5.12.02	17.1.03
t-APC1	Stage 3 column leachate	18.11.02	17.1.03	5.12.02	bottle broken
APC2	Stage 3 column leachate	18.11.02	17.1.03	5.12.02	17.1.03
Blank	Stage 3 column leachate	18.11.02	17.1.03	5.12.02	bottle broken



# Appendix G: Results of List 1 trace organic scan on solid MSWI residues

<b>Site 1 Untreated bottom ash</b>	<b>Semi-quantitative mg/kg</b>
1. Trichloroethylene	6.8±2.7
2. 1,2-Butadiene, 1,1-dichloro-	0.2±0.1
3. Toluene	0.2±0.1
4. Ethane, 1,1,2-trichloro-	2.8±1.1
5. Tetrachloroethylene	2.0±0.8
6. Furfural	0.2±0.1
7. Benzene, chloro-	0.4±0.2
8. Cyclobutene, 3,4-dichloro-	0.2±0.1
9. 1,3-Butadiene, 1,4-dichloro-	0.4±0.2
10. 1-Propene, 1,2,3-trichloro-	0.2±0.1
11. Benzocyclobutane	0.6±0.2
12. 1-Propene, 1,2,3,3-tetrachloro-	0.4±0.2
13. Ethane, 1,1,2,2-tetrachloro-	5.0±2.0
14. Benzaldehyde	1.2±0.5
15. Ethane, pentachloro-	0.6±0.2
16. 1-Hexanol, 2-ethyl-	0.4±0.2
17. Limonene	0.6±0.2
18. D-Limonene	0.6±0.2
19. Benzene, 1,2-dichloro-	0.6±0.2
20. 1,3-Butadiene, 1,1,3,4-tetrachloro-	0.6±0.2
21. Benzene, 1,2,3-trichloro-	0.4±0.2
22. 1,3-Butadiene, pentachloro-	0.2±0.1
23. Benzene, 1,2,4-trichloro-	1.4±0.6
24. Naphthalene	0.4±0.2
25. Benzene, 1,2,4,5-tetrachloro-	0.4±0.2
26. 2-Pentadecanone, 6,10,14-trimethyl-	0.6±0.2
27. Cyclic octa-atomic sulfur	0.2±0.1
28. Oxirane, hexadecyl-	0.8±0.3
29. 1-Eicosanol	0.4±0.2

Site2 Untreated bottom ash	Semi-quantitative mg/kg
1. Trichloroethylene	57.8±23.1
2. 1-Propene, 1,3-dichloro-, (Z)-	1.4±0.6
3. 1,3-Butadiene, 1,4-dichloro-	1.0±0.4
4. Cyclobutene, 3,4-dichloro-	1.0±0.4
5. 1,3-Dichloroallene	5.0±2.0
6. Ethane, 1,1,2-trichloro-	20.6±8.2
7. Cyclobutene, 3,4-dichloro-	1.4±0.6
8. Tetrachloroethylene	20.4±8.2
9. Furfural	1.0±0.4
10. Benzene, chloro-	8.6±3.4
11. 1,3-Butadiene, 1,4-dichloro-	2.6±1.0
12. Ethylbenzene	0.6±0.2
13. 1-Propene, 1,2,3-trichloro-, (Z)-	4.4±1.8
14. Styrene	8.0±3.2
15. Cyclopropene, tetrachloro-	0.6±0.2
16. Ethane, 1,1,2,2-tetrachloro-	88.8±35.5
17. Benzaldehyde	1.4±0.6
18. Ethane, pentachloro-	5.4±2.2
19. Benzene, 1,3-dichloro-	0.6±0.2
20. Phenol	0.4±0.2
21. Benzene, (1-methoxyethyl)-	0.4±0.2
22. 1-Hexanol, 2-ethyl-	0.6±0.2
23. Cyclopropane, pentachloro-	1.2±0.5
24. Benzene, 1-chloro-4-ethynyl-	4.6±1.8
25. Acetophenone	1.4±0.6
26. 1,3-Butadiene, 1,1,3,4-tetrachloro-	23.8±9.5
27. Benzene, 1,2,3-trichloro-	10.8±4.3
28. 1,3-Butadiene, pentachloro-	3.8±1.5

Sample 287827 Site2 Raw BA (continued)	Semi-Quant mg/kg
29. 1,3-Cyclopentadiene, 1,2,3,4-tetrachloro-	1.0±0.4
30. Benzoic Acid	0.8±0.3
31. Benzene,1,4-diethynyl-	0.4±0.2
32. Naphthalene	2.0±0.8
33. Benzene, 1,2,4,5-tetrachloro-	14.8±5.9
34. Naphthalene, 2-chloro-	1.8±0.7
35. Benzene, pentachloro-	4.0±1.6
36. 3-Hexadecene, (Z)-	0.8±0.3
37. Hexadecane	0.4±0.2
38. Naphthalene, 1,2-dichloro-	1.2±0.5
39. Benzene, 1,1'-(1,3-propanediyl)bis-	0.6±0.2
40. Methyl tetradecanoate	0.8±0.3
41. Naphthalene, 2,3,6-trichloro-	0.4±0.2
42. Naphthalene, 2,3,6-trichloro-	2.0±0.8
43. Naphthalene, 2,3,6-trichloro-	2.0±0.8
44. Anthracene	1.0±0.4
45. 1,14-Tetradecanediol	0.4±0.2
46. 1-Octadecene	0.6±0.2
47. Naphthalene, 1,2,3,4-tetrachloro-	1.6±0.6
48. Hexadecanoic acid, methyl ester	12.2±4.9
49. n-Hexadecanoic acid	62.2±24.9
50. Naphthalene, 2-phenyl-	0.6±0.2
51. 11-Octadecenoic acid, methyl ester, (Z)-	22.8±9.1
52. Ethyl Oleate	4.6±1.8
53. 9-Octadecenoic acid, (E)-	49.6±19.8
54. Octadecanoic acid	25.2±10.1
55. 1,1':3',1"-Terphenyl, 5'-phenyl-	1.4±0.6
56. 3-Chloro-17-(1,5-dimethylhexyl)-10,13-dimethyl-2,3,4,7,8,9,10,11,12,13,14,15,16,17-tetradecahydro-1H-cyclopenta[a]phenanthrene	27.2±10.9

Site3 Untreated bottom ash	Semi-quantitative mg/kg
1. 1,2-Propadiene, 1,1-dichloro-	30± 12
2. 1-Propene, 1,3-dichloro-, (E)-	120± 48
3. 1,3-Butadiene, 1,4-dichloro-	102± 40
4. 1,3-Dichloroallene	160± 64
5. Tetrachloroethylene	1444± 577
6. Benzene, chloro-	38± 15
7. Cyclobutene, 3,4-dichloro-	128± 51
8. 1-Propene, 1,2,3-trichloro-, (Z)-	180± 72
9. Furfural	22± 8
10. Benzene, chloro-	542± 216
11. Ethane, 1,1,1,2-tetrachloro-	168± 67
12. Phenylethyne	94± 37
13. Benzocyclobutane	868± 347
14. Cyclopropene, tetrachloro-	88± 35
15. 1,2-Butadiene, 1,1,4-trichloro-	58± 23
16. Ethane, 1,1,2,2-tetrachloro-	4020± 1608
17. Benzaldehyde	198± 79
18. à-Methylstyrene	24± 9
19. Ethane, pentachloro-	394± 157
20. 1-Propene, 1,2,3,3-tetrachloro-	46± 18
21. Benzene, 1,2-dichloro-	998± 399
22. Benzene, 1-chloro-4-ethynyl-	236± 94
23. 1-Propene, pentachloro-	22± 8
24. Benzene, 1,3-dichloro-	96± 38
25. 1,3-Butadiene, 1,1,3,4-tetrachloro-	840± 336
26. Benzene, 1,2,4-trichloro-	572± 228
27. 1,3-Butadiene, pentachloro-	212± 84
28. Naphthalene	26± 10

Site3 Untreated bottom ash (continued)	Semi-quantitative mg/kg
29. 1,3-Cyclopentadiene, 1,2,3,4-tetrachloro-	28± 11
30. Benzene, 1,2,4-trichloro-	2442± 976
31. Naphthalene	68± 27
32. Benzene, 1,2,3-trichloro-	882± 352
33. 2,6-Dichlorostyrene	76± 30
34. Benzene, 1,2-dichloro-4-(chloromethyl)-	22± 8
35. Benzene, 1,2,4,5-tetrachloro-	734± 293
36. Benzene, 2,4-dichloro-1-(chloromethyl)-	52± 20
37. Benzene, 1,4-dichloro-2-(2-chloroethenyl)-	30± 12
38. Naphthalene, 2-chloro-	146± 58
39. Benzene, 1-chloro-4-(trichloromethyl)-	22± 8
40. Benzene, 1,4-dichloro-2-(2-chloroethenyl)-	68± 27
41. Benzene, pentachloro-	258± 103
42. Naphthalene, 1,4-dichloro-	250± 100
43. Naphthalene, 2,3,6-trichloro-	180± 72
44. Hexadecanal	36± 14
45. 2-Pentadecanone, 6,10,14-trimethyl-	232± 92
46. Naphthalene, 1,3,5,7-tetrachloro-	86± 34
47. Hexadecanoic acid, methyl ester	120± 48
48. Naphthalene, 1,2,3,4-tetrachloro-	172± 68
49. n-Hexadecanoic acid	74± 29
50. Naphthalene, 2-phenyl-	20± 8
51. 9-Octadecenoic acid (Z)-, methyl ester	114± 45
52. Pyrene	22± 8
53. 1,14-Tetradecanediol	20± 8
54. Anthracene, 9,10-dichloro-	28± 11

Site 1 Carbonated bottom ash	Semi-quantitative mg/kg
1. Toluene	0.4±0.2
2. Ethane, 1,1,2-trichloro-	0.2±0.1
3. Furfural	0.2±0.1
4. Bicyclo[4.2.0]octa-1,3,5-triene	0.2±0.1
5. Ethane, 1,1,2,2-tetrachloro-	0.4±0.2
6. Benzaldehyde	0.6±0.2
7. Limonene	0.6±0.2
8. Naphthalene	0.2±0.1
9. 2-Pentadecanone, 6,10,14-trimethyl-	0.4±0.2
10. Hexadecanoic acid, methyl ester	0.4±0.2
11. 9-Octadecenoic acid (Z)-, methyl ester	0.8±0.3
12. Phytol	0.8±0.3
13. Cyclic octatomic sulfur	1.6±0.6
14. 2-Propenoic acid, 3-(4-methoxyphenyl)-, 2-ethylhexyl ester	0.4±0.2
15. Nonanedioic acid, bis(2-ethylhexyl) ester	1.0±0.4
16. Squalene	1.0±0.4
17. Pentadecanal-	0.4±0.2

Site2 Carbonated bottom ash	Semi-quantitative mg/kg
1. Trichloroethylene	0.6±0.2
2. Toluene	0.4±0.2
3. Ethane, 1,1,2-trichloro-	0.2±0.1
4. Hexanal	0.4±0.2
5. Furfural	0.8±0.3
6. Styrene	0.6±0.2
7. Ethane, 1,1,2,2-tetrachloro-	0.6±0.2
8. 5-methyl furfural	0.2±0.1
9. Benzaldehyde	1.0±0.4
10. Phenol	0.2±0.1
11. 1-Hexanol, 2-ethyl-	0.2±0.1
12. D-Limonene	1.2±0.5
13. Acetophenone	0.2±0.1
14. Nonanal	0.2±0.1
15. Naphthalene	0.6±0.2
16. Ethanol, 2-phenoxy-	0.2±0.1
17. 1,4:3,6-Dianhydro-à-d-glucopyranose	0.4±0.2
18. 2-Undecenal	0.2±0.1
19. Biphenyl	0.4±0.2
20. 1-Hexanone, 1-phenyl-	0.2±0.1
21. 1-Octadecene	0.2±0.1
22. 1,3-Diphenylpropane	0.2±0.1
23. 1-Octadecene	0.2±0.1
24. Phenanthrene	0.4±0.2
25. 2-Pentadecanone, 6,10,14-trimethyl-	0.4±0.2
26. Caffeine	0.2±0.1
27. Hexadecanenitrile	0.2±0.1
28. Hexadecanoic acid, methyl ester	0.4±0.2



Site2 Carbonated bottom ash (continued)	Semi-quantitative mg/kg
29. n-Hexadecanoic acid	0.8±0.3
30. Dibutyl phthalate	0.2±0.1
31. 1-Octadecene	0.2±0.1
32. 2-Phenylnaphthalene	0.2±0.1
33. 1,15-Pentadecanediol	0.2±0.1
34. 1-Nonadecene	0.2±0.1
35. 9-Octadecenoic acid (Z)-, methyl ester	1.0±0.4
36. Fluoranthene	0.4±0.2
37. Ethyl Oleate	0.6±0.2
38. Pyrene	0.4±0.2
39. Parsol MCX	0.4±0.2
40. 1-Nonadecene	0.4±0.2
41. Bisphenol A	0.2±0.1
42. Phenanthrene, 2,4,5,7-tetramethyl-	0.4±0.2
43. 1,15-Pentadecanediol	0.4±0.2
44. 1,3,5-Triphenylbenzene	0.6±0.2

Site3 Carbonated bottom ash	Semi-quantitative mg/kg
1. Ethane, 1,1,2-trichloro-	0.4±0.2
2. Styrene	0.4±0.2
3. Ethane, 1,1,2,2-tetrachloro-	0.8±0.3
4. Benzaldehyde	1.0±0.4
5. 2-Pentadecanone, 6,10,14-trimethyl-	1.4±0.6
6. 3,7,11,15-Tetramethyl-2-hexadecen-1-ol	0.4±0.2
7. 9-Octadecenoic acid (Z)-, methyl ester	0.4±0.2
8. 3,7,11,15-Tetramethyl-2-hexadecen-1-ol	4.4±1.8
9. Cyclic octaatomic sulfur	1.0±0.4
10. 9,12-Octadecadienoic acid, ethyl ester	1.8±0.7
11. Ethyl 9-octadecenoate, (E)-	5.4±2.2
12. Hexadecanamide	1.0±0.4
13. Bisphenol A	0.4±0.2
14. 9-Octadecenamide, (Z)-	0.6±0.2
15. Pentadecanal-	1.2±0.5

<b>Site 1 Untreated APC residues</b>	<b>Semi-quantitative mg/kg</b>
1. Trichloroethylene	9.0±3.6
2. 1,3-Dichloroallene	0.8±0.3
3. Toluene	0.4±0.2
4. Ethane, 1,1,2-trichloro-	2.4±1.0
5. Tetrachloroethylene	1.8±0.7
6. Benzene, chloro-	1.0±0.4
7. 1,3-Butadiene, 1,4-dichloro-	0.2±0.1
8. Ethane, 1,1,2,2-tetrachloro-	15.0±6.0
9. Ethane, pentachloro-	0.4±0.2
10. 1,3-Butadiene, 1,1,3,4-tetrachloro-	0.4±0.2
11. Benzene, 1,4-dichloro-	2.2±0.9
12. Benzene, 1-chloro-4-ethynyl-	0.8±0.3
13. Benzene, 1,2-dichloro-	0.2±0.1
14. 1,3-Butadiene, 1,1,3,4-tetrachloro-	3.4±1.4
15. 1,3-Butadiene, 1,1,3,4-tetrachloro-	1.0±0.4
16. Benzene, 1,2,3-trichloro-	1.2±0.5
17. 1,3-Butadiene, pentachloro-	0.4±0.2
18. Benzene, 1,2,4-trichloro-	6.2±2.5
19. Naphthalene	0.2±0.1
20. Benzene, 1,2,4,5-tetrachloro-	1.2±0.5
21. Benzene, pentachloro-	0.4±0.2
22. Naphthalene, 2,3-dichloro-	0.2±0.1
23. Naphthalene, 1,4-dichloro-	0.2±0.1
24. Hexanedioic acid, bis(2-ethylhexyl) ester	0.6±0.2

<b>Site 2 Untreated APC residues</b>	<b>Semi-quantitative mg/kg</b>
1. Trichloroethylene	124.8±49.9
2. Chloriodomethane	2.2±0.9
3. 1,3-Dichloroallene	13.8±5.5
4. 1,3-Butadiene, 1,4-dichloro-	1.0±0.4
5. Toluene	1.6±0.6
6. 1-Propene, 1,3-dichloro-, (E)-	3.4±1.4
7. Ethane, 1,1,2-trichloro-	24.2±9.7
8. Tetrachloroethylene	34.4±13.8
9. 1-Propene, 1,2,3-trichloro-, (Z)-	14.0±5.6
10. Benzene, chloro-	19.0±7.6
11. 1,3-Butadiene, 1,4-dichloro-	4.2±1.7
12. Phenylethyne	1.4±0.6
13. 1-Propene, 1,2,3-trichloro-, (Z)-	17.8±7.1
14. Ethane, 1,1,2,2-tetrachloro-	120.8±48.3
15. 1-Propene, 1,2,3-trichloro-	1.0±0.4
16. Benzene, 1,2-dichloro-	0.4±0.2
17. 2-Cyclopenten-1-one, 3-chloro-	0.2±0.1
18. Ethane, pentachloro-	8.6±3.4
19. Benzene, 1,3,5-trimethyl-	0.2±0.1
20. 1-Propene, 1,2,3,3-tetrachloro-	1.0±0.4
21. Benzene, 1,3-dichloro-	14.6±5.8
22. 1,3-Butadiene, 1,1,3,4-tetrachloro-	5.6±2.2
23. Benzene, 1,4-dichloro-	46.2±18.5
24. Benzene, 1-chloro-4-ethynyl-	7.2±2.9
25. Silane, tetrachloro-	4.4±1.8
26. Benzene, 1-chloro-4-ethynyl-	7.4±3.0
27. Benzene, (2-chloroethenyl)-, (Z)-	1.0±0.4
28. 1-Propene, pentachloro-	3.0±1.2

Site 2 Untreated APC residues (continued)	Semi-quantitative mg/kg
29. 1,3-Butadiene, 1,1,3,4-tetrachloro-	67.6±27.0
30. Benzene, dichloromethyl-	0.8±0.3
31. Benzene, 1,2,3-trichloro-	45.4±18.2
32. 1,3-Butadiene, pentachloro-	11.0±4.4
33. 1,3-Cyclopentadiene, 1,2,3,4-tetrachloro-	3.4±1.4
34. 4,5-Diamino-6-hydroxypyrimidine	0.6±0.2
35. Benzene, 1,2,4-trichloro-	144.0±57.6
36. Benzene, 1-chloro-4-(chloromethyl)-	1.8±0.7
37. Naphthalene	2.0±0.8
38. Benzene, 1,4-dichloro-2-ethenyl-	1.0±0.4
39. Benzene, 1,3,5-trichloro-	2.8±1.1
40. 2,6-Dichlorostyrene	1.8±0.7
41. Benzene, 1,2,4,5-tetrachloro-	1.0±0.4
42. Benzene, 1,2,4-trichloro-3-methyl-	0.4±0.2
43. Benzene, 2,4-dichloro-1-(chloromethyl)-	1.6±0.6
44. Benzene, 1,2,4,5-tetrachloro-	68.2±27.3
45. Benzene, 2,4-dichloro-1-(chloromethyl)-	3.0±1.2
46. Naphthalene, 2-chloro-	3.4±1.4
47. Benzene, 2,4-dichloro-1-(2-chloroethenyl)-	4.8±1.9
48. Benzene, 1-chloro-2-(trichloromethyl)-	1.2±0.5
49. Benzene, 1-chloro-3-(trichloroethenyl)-	0.4±0.2
50. Benzene, 1,4-dichloro-2-(2-chloroethenyl)-	3.0±1.2
51. Acenaphthylene	0.2±0.1
52. Benzene, pentachloro-	23.8±9.5
53. Benzene, 1,4-bis(trichloromethyl)-	2.8±1.1
54. Naphthalene, 1,5-dichloro-	6.2±2.5
55. 1,4-Dichloro-3-(trichlorovinyl)benzene	0.4±0.2
56. 1,1'-Biphenyl, 4,4'-dichloro- (PCB15)	0.2±0.1

Site 2 Untreated APC residues (continued)	Semi-quantitative mg/kg
57. Naphthalene, 1,3,7-trichloro-	0.8±0.3
58. 1,3-Cyclopentadiene, 1,2,3,4-tetrachloro-5-(dichloromethylene)-	1.6±0.6
59. Benzene, hexachloro-	1.2±0.5
60. Naphthalene, 1,3,7-trichloro-	4.6±1.8
61. Naphthalene, 1,2,3,4-tetrachloro-	2.6±1.0
62. 1,1'-Biphenyl, 2',3,4-trichloro- (PCB25)	0.4±0.2
63. Naphthalene, 1,3,5,7-tetrachloro-	4.6±1.8
64. Naphthalene, 1,2,3,4-tetrachloro-	5.2±2.1
65. n-Hexadecanoic acid	1.6±0.6
66. 1,1'-Biphenyl, 2,3',5,5'-tetrachloro- (PCB72)	0.4±0.2
67. Naphthalene, 1,4,6,7-tetrachloro-	0.2±0.1
68. 1,1'-Biphenyl, 2,3',4,4',5-pentachloro- (PCB114)	0.2±0.1
69. Anthracene, 9,10-dichloro-	0.4±0.2
70. 9H-Fluorene, 9-(dichloromethylene)-	0.6±0.2
71. 1,1'-Biphenyl, 2,2',3,3',5,6'-hexachloro- (PCB134/135)	0.4±0.2
72. 1,1'-Biphenyl, 2,3',4,4',5-pentachloro- (PCB114)	0.6±0.2
73. Hexanedioic acid, bis(2-ethylhexyl) ester	1.2±0.5

Site3 Untreated APC residues	Semi-quantitative mg/kg
1. Ethene, 1,2-dichloro-, (Z)-	1.4±0.6
2. 1-Buten-3-yne, 1-chloro-, (Z)-	6.6±2.6
3. Trichloroethylene	31.6±12.6
4. 1,3-Dichloroallene	3.0±1.2
5. Cyclobutene, 3,4-dichloro-	0.4±0.2
6. 1-Propene, 1,3-dichloro-, (Z)-	1.0±0.4
7. Ethane, 1,1,2-trichloro-	9.0±3.6
8. Tetrachloroethylene	6.4±2.6
9. 1-Propene, 1,2,3-trichloro-, (Z)-	3.4±1.4
10. Benzene, chloro-	4.2±1.7
11. 1,3-Butadiene, 1,4-dichloro-	1.4±0.6
12. Benzene, chloro-	0.2±0.1
13. 1-Propene, 1,2,3-trichloro-, (Z)-	4.2±1.7
14. Cyclopropene, tetrachloro-	0.4±0.2
15. Ethane, 1,1,2,2-tetrachloro-	17.4±7.0
16. Ethane, 1,1,2,2-tetrachloro-	46.0±18.4
17. Ethane, pentachloro-	2.4±1.0
18. Benzene, 1,3-dichloro-	10.0±4.0
19. Benzene, 1,4-dichloro-	9.8±3.9
20. 1-Propene, 1,2,3,3-tetrachloro-	2.2±0.9
21. Benzene, 1-chloro-4-ethynyl-	1.6±0.6
22. 1,3-Butadiene, 1,1,3,4-tetrachloro-	3.6±1.4
23. 1,3-Butadiene, 1,1,3,4-tetrachloro-	14.2±5.7
24. Benzene, 1,2-dichloro-	0.6±0.2
25. 1,3-Butadiene, pentachloro-	1.8±0.7
26. 1,3-Cyclopentadiene, 1,2,3,4-tetrachloro-	0.6±0.2
27. Benzene, 1,2,4-trichloro-	26.2±10.5
28. Naphthalene	0.4±0.2

Site3 Untreated APC residues (continued)	Semi-quantitative mg/kg
29. Benzene, 1,2,3-trichloro-	10.8±4.3
30. 2,6-Dichlorostyrene	0.4±0.2
31. Benzene, 1,2,4,5-tetrachloro-	10.4±4.2
32. Benzene, 1,2-dichloro-4-(chloromethyl)-	0.2±0.1
33. Benzene, 2,4-dichloro-1-(2-chloroethenyl)-	0.2±0.1
34. Naphthalene, 2-chloro-	1.2±0.5
35. Benzene, 1-chloro-2-(trichloromethyl)-	0.4±0.2
36. Benzene, 1,4-dichloro-2-(2-chloroethenyl)-	1.0±0.4
37. Benzene, 1,4-dichloro-2-(2-chloroethenyl)-	0.8±0.3
38. Benzene, pentachloro-	3.6±1.4
39. Benzene, 1,4-bis(trichloromethyl)-	0.8±0.3
40. Naphthalene, 1,5-dichloro-	1.8±0.7
41. Naphthalene, 2,3-dichloro-	1.8±0.7
42. Naphthalene, 1,4-dichloro-	0.6±0.2
43. Naphthalene, 1,3,7-trichloro-	1.6±0.6
44. Naphthalene, 2,3,6-trichloro-	0.6±0.2
45. Naphthalene, 1,2,3,4-tetrachloro-	1.8±0.7



<b>Site 1 Carbonated APC residues</b>	<b>Semi-quantitative mg/kg</b>
1. Toluene	0.4±0.2
2. Ethane, 1,1,2,2-tetrachloro-	0.2±0.1
3. Cyclic octaatomic sulfur	0.2±0.1

<b>Site2 Carbonated APC residues</b>	<b>Semi-quantitative mg/kg</b>
1. Trichloroethylene	2.0±0.8
2. Chloriodomethane	0.2±0.1
3. Toluene	1.6±0.6
4. Benzene, 1,3-dimethyl-	0.4±0.2
5. Ethane, 1,1,2,2-tetrachloro-	0.6±0.2
6. Benzene, 1,2,4-trichloro-	0.4±0.2
7. Naphthalene	0.2±0.1

<b>Site3 Carbonated APC residues</b>	<b>Semi-quantitative mg/kg</b>
1. Chloriodomethane	0.2±0.1
2. Cyclic octaatomic sulfur	0.8±0.3

# Appendix H: Analysis of LS 10 eluates for major ions, sanitary parameters and heavy metals

SITE 1 BOTTOM ASH		Eluates from untreated bottom ash					Eluates from carbonated bottom ash					Eluates from acid leaching test			
Stage 2 LS 10 eluates		BA 1					t-BA 1					BA 1 acid			
Determinand	units	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 4	Rep 5
pH	pH units	12.4	12.4	12.4	12.4	12.4	10.6	10.4	10.7	10.7	10.7	9.7	9.57	9.75	9.8
Conductivity	uS/cm	7850	7840	7830	7860	7700	1750	1760	1790	1760	1960	10400	10400	10400	10400
DOC	mg/l	27.1	24.8	24.8	23.3	23.8	19.5	19.9	20.6	20.2	20.5	48	52.6	51.6	51.6
COD	mg/l	79	82	80	78	77	65	61	66	63	68	180	233	203	257
BOD	mg/l	>47.7	44.5	42.3	40.3	39.8	21.6	23.2	24.1	23.2	25.9	68.7	68.9	68.7	72.4
NH4-N	mg/l	0.647	0.769	0.628	0.758	0.719	0.233	0.242	0.219	0.204	0.244	0.886	0.904	0.997	1.08
TKjN	mg/l											314	89.8	303	274
Cyanide (total)	mg/l	0.005	0.0065	0.0069	0.005	0.0055	0.005	<0.005	<0.005	<0.005	<0.005	<0.010	<0.010	<0.010	<0.010
Na	mg/l	81.5	84.3	70.7	70.9	69.8	73.4	73.8	77.2	75.9	86.3	90.8	88.7	94.7	101
K	mg/l	90.9	87.7	72.9	73.7	72.2	68.7	68.9	72.8	71.8	79.6	83.3	80.2	87.4	93.7
Ca	mg/l	808	739	737	766	741	245	245	248	236	281	2200	2140	2270	2290
Mg	mg/l	<0.30	<0.30	<0.30	<0.30	<0.30	0.339	0.365	0.326	0.33	0.417	23.7	31.2	26.7	22.3
Chloride	mg/l	164	193	164	162	161	185	187	193	189	193	198	194	197	200
SO4	mg/l	174	192	163	212	157	504	517	511	501	609	706	729	733	709
NOx-N	mg/l	<0.20	0.723	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	1180	1220	1130	1210
Alkalinity pH4.5 as CaCO3	mg/l							73	84.4	81.6	81.6	61.2	80.2	77.8	81.6
Total metals:															
As	ug/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	3.89	1.14	3.77	2.55
Hg	ug/l	<0.010	0.023	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	0.025	<0.010	<0.010
Cd	ug/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Cr	ug/l	15.2	68.2	19.5	14.2	12.9	32.8	32.7	27.7	31.1	19.9	26.3	24.5	36.6	29.4
Cu	ug/l	460	476	484	483	529	176	182	186	180	203	692	665	754	790
Pb	ug/l	4190	4210	3250	3030	4200	3.29	2.07	<1.00	<1.00	<1.00	5.1	3.46	2.5	3.5
Ni	ug/l	<5.00	<5.00	<5.00	<5.00	<5.00	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0
Zn	ug/l	1070	1110	981	1050	1090	11.7	11.3	<10.0	10	11.6	15.6	<10.0	<10.0	10.2
Sb	ug/l	<10.0	<10.0	<10.0	<10.0	<10.0	28.7	22.4	21.3	23.1	19.6	93.9	141	117	83.2
Mo	ug/l	53.7	49.2	56.6	59.6	55.4	67.9	68.8	71.5	69.9	75.5	115	99.6	114	111
V	ug/l	<10.0	<10.0	<10.0	<10.0	<10.0	18	17.4	17.9	17.2	16.7	43	44.3	46.3	47.3
Ba	ug/l	653	575	642	618	664	122	118	127	124	121	283	271	281	307
Tl	ug/l	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
Se	ug/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	2.76	3.1	2.15	2.88
Sn	ug/l	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0

SITE 2 BOTTOM ASH		Eluates from untreated bottom ash					Eluates from carbonated bottom ash					Eluates from acid leaching test			
Stage 2 LS 10 eluates		BA 2					t-BA 2					BA 2 acid			
Determinand	units	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 3	Rep 4	Rep 5
pH	pH units	12	12	12.1	12	12.1	9.72	9.74	9.77	9.8	9.85	9.12	9	9.06	9.06
Conductivity	uS/cm	3660	3790	3910	3730	3950	1900	1920	1870	1950	1980	7710	7930	8030	7970
DOC	mg/l	78.5	79.6	86	83.4	100	70.7	72.9	70	77.5	75.5	129	136	137	136
COD	mg/l	248	240	254	248	250	205	208	203	210	213	368	395	418	447
BOD	mg/l	120	140	135	140	88.4	94.9	96.9	103	100	85	177	192	191	192
NH4-N	mg/l	1.41	1.3	1.38	1.36	1.4	0.413	0.435	0.484	0.447	0.448	1.94	1.94	1.91	2.05
TKjN	mg/l	4.79	4.77	4.81	4.77	4.85	3.27	3.12	3.18	3.02	3.29	131	205	245	125
Cyanide (total)	mg/l	<0.005	<0.005	<0.005	<0.005	0.0096	<0.005	0.0053	<0.005	<0.005	<0.005	<0.010	<0.010	<0.010	<0.010
Na	mg/l	199	170	174	179	175	138	143	169	161	154	176	171	169	179
K	mg/l	124	107	111	116	113	78.5	81.8	96.7	92.1	88.5	106	103	102	108
Ca	mg/l	386	353	353	370	351	252	265	302	296	283	1500	1490	1520	1550
Mg	mg/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	12.7	24.9	22.6	21
Chloride	mg/l	300	297	301	300	313	328	319	322	324	335	341	350	344	341
SO4	mg/l	71.9	85.3	54	62.4	60.3	357	393	422	437	420	481	537	585	530
NOx-N	mg/l	0.618	0.632	0.706	0.661	0.669	0.857	0.871	0.832	0.88	0.875	776	796	792	794
Alkalinity pH4.5 as CaCO3	mg/l	521	567	600	551	589	176	171	174	142	171	122	119	122	120
Total metals:															
As	ug/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Hg	ug/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.011	<0.01	0.25
Cd	ug/l	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	0.516	<0.50	<0.50	<1.00	<1.00	<1.00	<1.00
Cr	ug/l	7.66	6.42	6.12	9.31	5.66	12.2	13.3	13.8	11.9	14.7	15.1	17.6	25.8	22.9
Cu	ug/l	981	901	866	956	928	524	559	661	607	618	1690	1520	1560	1560
Pb	ug/l	2020	1730	1610	1210	1190	5.27	4.66	5.55	6.86	4.84	21.5	16.9	18.7	23.2
Ni	ug/l	15.7	13.9	13.1	14.5	13.6	<5.00	<5.00	<5.00	<5.00	<5.00	<50.0	<50.0	<50.0	<50.0
Zn	ug/l	184	288	161	194	218	10	9.71	13.1	11	11.5	17.3	18.1	17.8	19
Sb	ug/l	17.1	14.8	17.2	15.1	12.2	74.1	101	102	90.8	83.8	115	178	166	196
Mo	ug/l	69.8	65.4	68.1	75.2	69.7	76.4	72.8	88.5	89.7	79	112	111	113	113
V	ug/l	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<10.0	<10.0	10.4	10.5
Ba	ug/l	699	608	679	673	607	109	109	128	130	126	261	256	271	263
Tl	ug/l	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<10.0	<10.0	<10.0	<10.0
Se	ug/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	1.22	1.05	<1.00
Sn	ug/l	<12.5	<12.5	<12.5	<12.5	<12.5	<12.5	<12.5	<12.5	<12.5	<12.5	<25.0	<25.0	<25.0	<25.0

SITE 3 BOTTOM ASH		Eluates from untreated bottom ash					Eluates from carbonated bottom ash					Eluates from acid leaching test			
Stage 2 LS 10 Eluates		BA 3					t-BA 3					BA 3 acid			
Determinand	units	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 2	Rep 3	Rep 4	Rep 5
pH	pH units	12.4	12.5	12.4	12.4	12.4	9.54	9.36	9.46	9.36	9.38	7.4	7.43	7.28	7.41
Conductivity	uS/cm	7760	7640	7730	7760	7820	1780	1900	1870	1820	1820	12500	12600	12400	12500
DOC	mg/l	62.5	60.2	62.5	58	61.7	53.9	58.4	55.2	55.4	55.2	116	114	97.6	117
COD	mg/l	177	167	176	168	173	150	163	158	153	158	485	580	399	412
BOD	mg/l	80.2	85.8	83.3	80.2	82.3	67.5	77.4	74.4	62.2	70.2	125	108	96.5	112
NH4-N	mg/l	0.704	1.15	1.42	1.13	1.17	0.352	0.359	0.331	0.316	0.334	3.51	3.2	2.95	3.1
TKjN	mg/l	5.92	5.6	5.77	7	5.55	3.53	3.81	3.67	3.67	4.21				
Cyanide (total)	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.0068	<0.005	0.0061	<0.005	<0.005
Na	mg/l	91.4	88.5	91.5	92	91.1	86.8	94	91.4	89.2	88.4	129	135	121	129
K	mg/l	73.8	71.3	73.9	109	73.6	61.3	65.8	64.4	62.9	62.3	94.4	98	102	93.7
Ca	mg/l	786	775	782	770	782	277	296	290	281	281	3000	3150	2790	3120
Mg	mg/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	67.8	76.2	73	77.6
Chloride	mg/l	186	180	186	183	186	202	217	213	206	207	209	209	210	202
SO4	mg/l	120	118	165	164	120	550	598	588	567	566	793	844	750	772
NOx-N	mg/l	<0.200	<0.200	<0.200	<0.200	<0.200	<0.200	<0.200	<0.200	<0.200	<0.200	9.39	8.16	8.99	8.03
Alkalinity pH4.5 as CaCO3	mg/l	2150	2100	2080	2050	2130	141	137	129	128	130	113	139	130	145
Total metals:															
As	ug/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	1.54	2.19	1.6	1.88
Hg	ug/l	<0.01	<0.01	0.011	0.012	<0.01	<0.01	<0.01	<0.01	<0.01	0.013	0.021	<0.010	0.082	<0.010
Cd	ug/l	0.157	<1.00	<1.00	<1.00	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	17.5	15.7	30.9	35.4
Cr	ug/l	10.6	14.4	13.8	12.3	14.2	14.8	16.7	19.1	16.1	19.1	10.6	13.4	<10.0	11.7
Cu	ug/l	1260	1200	1250	1260	1290	550	535	516	531	509	2120	2110	1750	2230
Pb	ug/l	1080	1160	993	2050	1180	1.59	1.79	2.02	2.18	1.64	9.73	10.5	17.6	22.3
Ni	ug/l	28.4	31.2	32.9	33.3	33.1	12	10.1	10.3	10.6	9.77	103	112	163	210
Zn	ug/l	688	627	592	880	670	12.1	11.9	11.9	11	12.5	3410	2380	8350	11200
Sb	ug/l	<1.00	<10.0	<10.0	<10.0	<10.0	66.1	67.8	68.4	73.1	69.7	164	161	136	166
Mo	ug/l	69.4	63.6	68.7	68.6	68.6	74	78.6	74.1	74.3	74.3	111	119	<100	102
V	ug/l	<5.00	<10.0	<10.0	<10.0	<10.0	15.2	15.9	10.3	16	16.6	<100	<100	<100	<100
Ba	ug/l	581	580	589	553	630	100	<100	<100	<100	<100	360	394	390	440
Tl	ug/l	<50.0	<10.0	<10.0	<10.0	<10.0	<5.00	<5.00	<5.00	<5.00	<5.00	<100	<100	<100	<100
Se	ug/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	1.75	1.23	2.1
Sn	ug/l	<2.50	<25.0	<25.0	<25.0	<25.0	<12.5	<12.5	<12.5	<12.5	<12.5	<50.0	<50.0	<50.0	<50.0

SITE 1 APC RESIDUE		Eluates from untreated APC residue					Eluates from carbonated APC residue					Eluates from acid leaching test			
Stage 2 LS 10 eluates		APC 1					t-APC 1					APC 1 acid			
Determinand	units	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3	Rep 5
pH	pH units	12.2	12.1	12.1	12.1	12.1	9.41	9.29	9.64	9.54	9.68	7.78	8.66	5.83	12.2
Conductivity	uS/cm	56700	56500	56600	56400	56300	49000	48700	49000	48800	49000	79400	79700	79500	56300
TOC	mg/l	5.4	5.4	4.2	5.8	4.2	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	23.8
COD	mg/l	29.2	25.2	27.2	25.2	33.2	<25.0	<25	<25.0	<25	<25	<25.0	<25.0	<25.0	54
BOD	mg/l						<5.70	<5.70	<5.70	<5.70	<5.70	<5.70	<5.70	<5.70	6.59
NH4-N	mg/l	0.179	0.176	0.139	0.147	0.158	0.187	0.2	0.18	0.201	0.19	0.395	0.474	0.436	0.322
TKjN	mg/l														
Cyanide (total)	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Na	mg/l	1670	1630	1660	1620	1630	1540	1550	1570	1550	1560	1780	1800	1800	1890
K	mg/l	2720	2660	2700	2650	2670	2490	2500	2520	2480	2490	2970	2640	2930	3090
Ca	mg/l	9540	9210	9500	9300	9440	7970	8010	8100	7970	8000	21400	18700	20900	11300
Mg	mg/l	<0.30	<0.30	<0.30	<0.30	<0.30	1.12	1.16	1.27	1.29	1.32	6.27	25.4	8.52	<0.30
Chloride	mg/l	18200	18100	19500	19700	19900	19200	18700	19200	19100	18200	17600	15900	20100	23100
SO4	mg/l	1750	1560	1850	1800	1850	1190	1210	1220	1200	1260	1300	998	1250	1990
NOx-N	mg/l	<0.20	<0.20	0.2	0.2	0.2	<0.20	<0.20	<0.20	<0.20	<0.20	6630	9.63	45.7	2.68
Alkalinity pH4.5 as CaCO3	mg/l						15.1								
Total metals:															
As	ug/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	1.57	1.07	8.79	<1.00
Hg	ug/l	0.428	1.12	0.265	0.469	0.252	1.55	1.71	1.5	1.62	1.56	0.29	0.146	1.59	0.65
Cd	ug/l	<100	<100	<100	<100	<100	28.3	21.4	27.9	32.3	28.1	151	285	165	<10.0
Cr	ug/l	<500	<500	<500	<500	<500	256	192	270	256	268	16.1	15.1	14.3	<50.0
Cu	ug/l	617	693	614	659	619	28.7	14.4	27.7	30	27.7	100	46.9	68.1	505
Pb	ug/l	138000	128000	147000	159000	149000	119	61.4	59.2	60.9	46.5	67.2	592	27.7	158000
Ni	ug/l	<500	<500	<500	<500	<500	<50.0	<50.0	52.6	59.8	61.7	213	250	268	<50.0
Zn	ug/l	7340	7380	7330	7410	7500	<100	<100	<100	107	<100	41.9	46.6	45.8	5940
Sb	ug/l	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	485	793	625	<100
Mo	ug/l	481	478	467	467	472	542	546	552	556	534	839	802	854	575
V	ug/l	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
Ba	ug/l	5170	5890	4890	4920	4510	2310	2400	2440	2360	2420	7380	6680	7070	5480
Tl	ug/l	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
Se	ug/l	1.05	1.05	1.49	1.05	2.05	1.37	1.43	1.15	1.25	1.35	16.8	15	15.5	1.75
Sn	ug/l	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<50.0	<50.0	<50.0	<50.0

SITE 2 APC RESIDUE		Eluates from untreated APC residue					Eluates from carbonated APC residue					Eluates from acid leaching test			
Stage 2 LS 10 eluates		APC 2					t-APC 2					APC 2 acid			
Determinand	units	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3	Rep 4
pH	pH units	12.2	12.1	12.1	12.2	12.1	9.8	9.67	9.57	9.71	9.67	11.5	9.97	9.77	9.31
Conductivity	uS/cm	42700	42800	42500	42700	42700	31000	31200	31300	31200	31300	79800	82400	82900	82700
DOC	mg/l	44.8	41.8	42.2	41.8	36.6	<2.00	<2.00	<2.00	2	<2.00	12.6	6	5.8	5.55
COD	mg/l	74.3	72.3	72.3	72.3	78	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0
BOD	mg/l	10.7	16.4	11.4	27.5	13.2	<5.70	<5.70	<5.70	<5.70	<5.70	<5.70	<5.70	<5.70	<5.70
NH4-N	mg/l	1.1	1.13	1.14	1.16	1.07	5.13	5.32	5.88	5.33	5.36	0.74	0.639	0.595	0.867
TKjN	mg/l	<1.00	<1.00	<1.00	<1.00	<1.00									
Cyanide (total)	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005		<0.005	<0.005	<0.005
Na	mg/l	1550	1250	1070	1370	1230	979	991	985	936	970	1180	1260	1200	1240
K	mg/l	1900	1510	1280	1700	1530	1140	1150	1120	1080	1140	1280	1400	1330	1370
Ca	mg/l	10000	8060	7080	9030	8210	5580	5600	5460	5250	5580	21400	24600	23300	23500
Mg	mg/l	<1.00	<1.00	<1.00	<1.00	<1.00	1.22	1.34	1.32	1.25	1.3	<0.30	9.37	10.3	34
Chloride	mg/l	14300	14400	14300	13600	14800	11700	11900	11700	11600	11800	14400	14600	15900	12400
SO4	mg/l	998	798	710	928	796	290	298	288	287	294	708	1330	1250	1330
NOx-N	mg/l											44.3	9.61	9.63	7.11
Alkalinity pH4.5 as CaCO3	mg/l	2430	2480	2480	2500	2500	76.6	61	51.6	60.2	61.4		49.1	39.2	26.7
Total metals:															
As	ug/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	6.89	3.84	3.77	2.55
Hg	ug/l	0.101	0.079	0.068	0.086	0.083	0.192	0.209	0.209	0.216	0.226	0.08	0.09	0.092	0.051
Cd	ug/l	<2.00	<2.00	<2.00	<2.00	<2.00	8.57	9.22	8.32	8.22	8.52	<10.0	<10.0	<10.0	15.1
Cr	ug/l	<10.00	<10.00	<10.00	11.2	11	6.76	6.24	7.52	6.04	8.88	<50.0	82	56.1	52
Cu	ug/l	49.6	36.5	30.6	42.7	40.6	10.5	10.4	9.97	9.81	9.78	72	34.4	15.6	14.5
Pb	ug/l	8450	6520	6840	8110	8130	2.88	2.16	1.31	<1.00	<1.00	16000	73.9	689	219
Ni	ug/l	<250	<10.0	<10.0	<10.0	<10.0	<250	<250	<250	<250	<250	<50.0	315	205	197
Zn	ug/l	5540	4160	3640	4630	4520	17.6	16.9	18.3	15.9	16	802	394	175	149
Sb	ug/l	<20.0	<20.0	<20.0	<20.0	<20.0	12	12.5	11.4	10.9	12.3	<100	<100	<100	127
Mo	ug/l	208	166	138	183	165	115	117	119	116	116	267	352	337	354
V	ug/l	<20.0	<20.0	<20.0	<20.0	<20.0	<10.0	<10.0	<10.0	<10.0	<10.0	<100	<100	<100	<100
Ba	ug/l	7030	5610	4990	6240	5700	2100	2120	2100	1940	1990	5690	4710	4700	4890
Tl	ug/l	<20.0	<20.0	<20.0	<20.0	<20.0	<10.0	<10.0	<10.0	<10.0	<10.0	<100	<100	<100	<100
Se	ug/l	7.87	6.44	6.94	7.56	7.27	2.05	2.05	2.15	2.27	2.35	5.39	10	9.03	7.74
Sn	ug/l	<50.0	<50.0	<50.0	<50.0	<50.0	<25.0	<25.0	<25.0	<25.0	<25.0	<50.0	<50.0	<50.0	<50.0

SITE 3 APC RESIDUE		Eluates from untreated APC residue					Eluates from carbonated APC residue					Eluates from acid leaching test			
Stage 2 LS 10 eluates		APC 3					t-APC 3					APC 3 acid			
Determinand	units	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3	Rep 5
pH	pH units	12.1	12.2	12.2	12.2	12.2	11.2	11.3	11.2	11.2	11.3	7.88	9.6	9.76	9.41
Conductivity	uS/cm	44500	44300	45000	44000	43900	34300	34300	34200	34400	34500	79400	79200	78900	79700
DOC	mg/l	13.4	12.4	11.8	9.4	10.4	5	<4.00	4	5	4.4	7.44	6.36	6	7.2
COD	mg/l	41	41	95	123	108	<25.0	<25.0	<25.0	<25.0	<25.0	<25.0	29	<26.0	<25.0
BOD	mg/l	5.97	20.5	20.4	13.7	19.7	<5.70	<5.70	<5.70	<5.70	<5.70	<5.70	<5.70	<5.70	<5.70
NH4-N	mg/l	2.55	1.74	1.7	1.76	1.77	1.31	1.29	1.33	1.93	1.7	5.31	3.81	3.84	4.03
TKjN	mg/l	5.41	5.47	5.51	5.41	4.95									
Cyanide (total)	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.0065	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Na	mg/l	1230	1200	1230	1210	1230	1040	1030	1040	1030	1040	1250	1290	1250	1260
K	mg/l	2360	2290	2160	2310	2290	1930	1960	1930	1940	1950	2310	2300	2070	2360
Ca	mg/l	7520	7250	6870	7330	7250	5600	5670	5590	5600	5650	22600	22700	20500	23400
Mg	mg/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	188	15.5	9.88	38.8
Chloride	mg/l	14800	14700	14500	14700	14200	12500	12600	12600	12700	12800	11400	3350	12700	12800
SO4	mg/l	658	607	661	656	660	605	609	566	562	620	1500	1110	989	1270
NOx-N	mg/l	1.91	1.97	1.94	1.92	1.92	0.571	0.541	0.517	0.309	0.375	173	14.9	18.6	9.37
Alkalinity pH4.5 as CaCO3	mg/l	2950	2780	2850	2730	2730	154	158	140	157	178			88.4	63.7
Total metals:															
As	ug/l	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<5.00	<25.0	8.09	6.02
Hg	ug/l	1.04	1.48	1.35	1.31	1.28	0.121	0.114	0.121	0.118	0.116	4.98	1.14	0.184	1.52
Cd	ug/l	<50.0	<50.0	<50.0	<50.0	<50.0	2.04	2.02	2.03	2.12	<2.00	2520	17.3	19.2	49.6
Cr	ug/l	<250	<250	<250	<250	<250	88.4	82.4	81.8	78.3	77.4	<50.0	<50.0	<50.0	<50.0
Cu	ug/l	352	352	292	356	338	229	227	219	213	206	134	107	110	69.2
Pb	ug/l	46400	48300	48000	53100	53000	1230	1320	1320	1030	1430	<10.0	<10.0	<10.0	<10.0
Ni	ug/l	<250	<250	<250	<250	<250	103	113	109	109	109	309	186	163	175
Zn	ug/l	7910	7970	10000	7900	7620	391	370	341	293	359	1180	112	128	112
Sb	ug/l	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	1030	130	372	901
Mo	ug/l	386	366	387	378	386	297	288	291	290	286	580	595	618	682
V	ug/l	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<100	<100	<100	<100
Ba	ug/l	3760	4900	6790	3640	4760	3350	3340	3400	3400	3340	4620	4770	4860	4850
Tl	ug/l	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	<100	<100	<100	<100
Se	ug/l	21.2	19.4	21.4	18.6	18.7	5.98	5.67	5.47	4.84	5.25	272	98.7	139	109
Sn	ug/l	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0



# Appendix I: Analytical results for dioxins and furans in LS 10 eluates

Dioxin results on MSWI residue eluates		26/06/02	15/07/02	18/07/02	26/06/02	15/07/02	18/07/02	12/09/02	12/09/02	11/10/02	blanks	blanks	blanks	blanks	blanks	blanks		
Dioxin analysis by EA laboratory, Leeds		Bottom ash eluates at LS 10										26/06/02	26/06/02	15/07/02	15/07/02	18/07/02	18/07/02	
Results received 13.02.03		untreated			carbonated			acid leached			BA1/	APC1/	BA2/	t-BA2/	BA3/	APC3/		
Analyte	Units	BA 1	BA2	BA3	t-BA1	t-BA2	t-BA3	a-BA1	a-BA2	a-BA3	t-BA1	t-APC1	APC2	t-APC2	t-BA3	t-APC3		
1,2,3,4,6,7,8-heptachlorodibenzo-p-dioxin	pg/l	<4.110	<2.968	<1.529	<3.100	<3.811	<1.257	<14.80	<8.630	<4.490	<1.420	<b>7.52</b>	<3.805	<12.56	<2.724	<26.61		
1,2,3,4,6,7,8-heptachlorodibenzofuran	pg/l	<0.735	<2.102	<2.115	<1.410	<1.177	<0.304	<5.360	<2.290	<1.250	<1.440	<3.430	<2.143	<2.737	<1.941	<9.600		
1,2,3,4,7,8,9-heptachlorodibenzofuran	pg/l	<1.620	<1.220	<0.925	<1.310	<0.862	<1.017	<9.780	<6.710	<4.340	<0.422	<2.380	<2.015	<2.852	<1.995	<1.346		
1,2,3,4,7,8-hexachlorodibenzo-p-dioxin	pg/l	<0.683	<0.430	<0.518	<0.342	<0.998	<1.305	<4.590	<10.30	<4.910	<1.810	<b>2.88</b>	<1.777	<2.883	<1.327	<0.775		
1,2,3,4,7,8-hexachlorodibenzofuran	pg/l	<0.818	<0.446	<0.355	<0.342	<0.626	<0.295	<3.420	<2.710	<2.070	<0.734	<1.440	<1.970	<2.769	<0.604	<0.638		
1,2,3,6,7,8-hexachlorodibenzo-p-dioxin	pg/l	<0.463	<1.751	<0.312	<0.512	<0.671	<0.990	<17.40	<10.50	<2.210	<2.710	<2.230	<0.721	<3.246	<0.986	<1.170		
1,2,3,6,7,8-hexachlorodibenzofuran	pg/l	<0.494	<0.814	<0.384	<0.512	<0.333	<0.129	<4.230	<3.300	<0.700	<0.913	<3.580	<1.104	<1.483	<0.224	<1.027		
1,2,3,7,8,9-hexachlorodibenzo-p-dioxin	pg/l	<1.210	<1.096	<0.242	<1.170	<1.838	<1.189	<5.970	<16.30	<4.030	<1.530	<3.750	<3.505	<2.336	<2.287	<1.409		
1,2,3,7,8,9-hexachlorodibenzofuran	pg/l	<0.780	<0.405	<0.307	<0.240	<0.462	<0.569	<14.90	<2.650	<1.150	<0.745	<1.800	<2.580	<2.679	<2.011	<1.195		
1,2,3,7,8-pentachlorodibenzo-p-dioxin	pg/l	<0.699	<0.884	<0.242	<0.452	<0.539	<0.974	<11.00	<7.490	<1.610	<1.580	<3.190	<4.210	<1.988	<1.773	<1.689		
1,2,3,7,8-pentachlorodibenzofuran	pg/l	<1.060	<0.694	<0.737	<1.020	<0.428	<0.605	<17.10	<3.180	<0.863	<0.787	<b>3.81</b>	<5.138	<1.132	<0.602	<0.922		
2,3,4,6,7,8-hexachlorodibenzofuran	pg/l	<0.709	<0.817	<0.332	<1.030	<0.290	<0.306	<2.730	<1.790	<1.540	<0.358	<2.360	<2.286	<1.336	<0.547	<0.337		
2,3,4,7,8-pentachlorodibenzofuran	pg/l	<0.352	<0.925	<0.773	<1.040	<0.688	<0.152	<5.180	<3.660	<1.540	<1.300	<b>3.72</b>	<2.258	<2.046	<1.542	<1.609		
2,3,7,8-tetrachlorodibenzo-p-dioxin	pg/l	<0.663	<0.426	<0.821	<0.759	<0.932	<1.011	<2.030	<1.880	<0.577	<0.329	<1.020	<2.668	<6.172	<2.680	<0.305		
2,3,7,8-tetrachlorodibenzofuran	pg/l	<0.407	<2.071	<0.224	<1.020	<0.207	<0.301	<7.330	<2.650	<0.155	<0.432	<1.570	<2.125	<1.318	<2.129	<1.220		
octachlorodibenzo-p-dioxin	pg/l	<b>12.2</b>	<6.540	<2.527	<b>7.16</b>	<29.77	<3.329	<27.70	<18.90	<6.380	<6.840	<b>21.5</b>	<2.762	<5.090	<41.43	<188.4		
octachlorodibenzofuran	pg/l	<1.150	<1.200	<1.639	<0.6160	<1.633	<2.747	<21.00	<10.50	<2.990	<2.030	<1.800	<11.29	<30.30	<1.963	<3.803		
		26/06/02	15/07/02	18/07/02	26/06/02	15/07/02	18/07/02	11/10/02	11/10/02	11/10/02	07/11/02	07/11/02	07/11/02	18/11/02	18/11/02	18/11/02	18/11/02	
		APC eluates at LS 10										BA column test eluates			APC column test eluates			blank
		untreated			carbonated			acid leached			untreated		carb't'd	untreated		carb't'd		
		APC1	APC2	APC3	t-APC1	t-APC2	t-APC3	a-APC1	a-APC2	a-APC3	BA1	BA2	t-BA2	APC1	APC2	t-APC1		
1,2,3,4,6,7,8-heptachlorodibenzo-p-dioxin	pg/l	<2.540	<1.673	<4.425	<0.472	<1.567	<5.032	<1.660	<3.460	<1.450	<13.30	<2.010	<16.80	<18.50	<1.990	no result	no result	
1,2,3,4,6,7,8-heptachlorodibenzofuran	pg/l	<0.347	<0.462	<2.723	<0.391	<4.072	<1.453	<0.576	<2.060	<2.680	<2.240	<2.520	<1.320	<9.060	<2.270	no result	no result	
1,2,3,4,7,8,9-heptachlorodibenzofuran	pg/l	<2.210	<1.970	<2.654	<0.618	<0.574	<6.363	<0.390	<1.060	<3.390	<7.390	<1.530	<3.680	<21.60	<9.960	no result	no result	
1,2,3,4,7,8-hexachlorodibenzo-p-dioxin	pg/l	<0.519	<1.987	<0.500	<0.383	<1.165	<1.892	<1.100	<2.130	<3.550	<5.250	<3.490	<1.670	<26.00	<3.200	no result	no result	
1,2,3,4,7,8-hexachlorodibenzofuran	pg/l	<0.751	<0.932	<0.498	<0.265	<0.528	<1.990	<0.896	<1.350	<2.430	<4.540	<1.630	<1.370	<6.410	<1.720	no result	no result	
1,2,3,6,7,8-hexachlorodibenzo-p-dioxin	pg/l	<0.555	<1.362	<0.545	<0.918	<0.677	<1.986	<1.410	<1.680	<2.590	<3.210	<1.940	<3.720	<16.00	<1.610	no result	no result	
1,2,3,6,7,8-hexachlorodibenzofuran	pg/l	<0.639	<0.594	<0.497	<0.387	<0.237	<1.022	<0.347	<0.482	<1.060	<1.440	<0.575	<0.902	<8.110	<2.110	no result	no result	
1,2,3,7,8,9-hexachlorodibenzo-p-dioxin	pg/l	<0.341	<1.749	<1.378	<1.270	<0.869	<0.960	<1.250	<2.050	<1.900	<2.760	<3.050	<4.090	<9.290	<4.400	no result	no result	
1,2,3,7,8,9-hexachlorodibenzofuran	pg/l	<0.647	<0.504	<0.750	<0.196	<1.384	<2.448	<0.624	<1.030	<2.810	<6.860	<3.010	<2.330	<14.70	<0.692	no result	no result	
1,2,3,7,8-pentachlorodibenzo-p-dioxin	pg/l	<0.707	<1.595	<0.558	<0.679	<0.867	<5.356	<1.440	<0.606	<0.896	<7.450	<5.000	<2.290	<21.10	<2.550	no result	no result	
1,2,3,7,8-pentachlorodibenzofuran	pg/l	<0.508	<0.816	<1.201	<0.345	<0.331	<2.431	<0.774	<2.170	<2.180	<2.960	<1.870	<0.893	<7.640	<0.378	no result	no result	
2,3,4,6,7,8-hexachlorodibenzofuran	pg/l	<0.683	<0.429	<0.309	<0.454	<0.093	<1.004	<0.069	<0.863	<0.781	<2.240	<1.740	<1.280	<6.960	<2.270	no result	no result	
2,3,4,7,8-pentachlorodibenzofuran	pg/l	<0.706	<0.762	<0.924	<0.482	<0.459	<1.846	<0.401	<0.492	<0.866	<3.150	<2.080	<1.280	<5.860	<1.020	no result	no result	
2,3,7,8-tetrachlorodibenzo-p-dioxin	pg/l	<1.130	<0.834	<4.800	<0.507	<0.820	<4.029	<0.287	<1.700	<2.130	<2.930	<0.244	<0.600	<4.190	<1.280	no result	no result	
2,3,7,8-tetrachlorodibenzofuran	pg/l	<0.418	<0.3888	<0.530	<0.580	<0.216	<1.273	<0.236	<0.716	<2.600	<0.523	<0.645	<0.742	<5.380	<0.996	no result	no result	
octachlorodibenzo-p-dioxin	pg/l	<4.520	<5.237	<6.979	<1.050	<6.065	<18.08	<2.900	<2.830	<7.220	<21.10	<8.090	<8.630	<62.90	<8.090	no result	no result	
octachlorodibenzofuran	pg/l	<1.210	<2.578	<4.642	<1.840	<5.076	<4.325	<0.909	<2.780	<3.390	<5.600	<2.640	<6.550	<24.00	<11.90	no result	no result	

# Appendix J: List 1 trace organics in LS 10 eluates

Results of a screening technique conducted by the EA  
National Laboratory Service, Nottingham

All results are given in  $\mu\text{g/l}$  in the eluate as submitted to the  
laboratory

Compound	Semi-quantitative µg/l
<b>Site 1 untreated bottom ash</b>	
1. Ethylisoamylketone	234± 93
2. Benzaldehyde	52± 20
3. 1-Hexanol, 2-ethyl-	74± 29
4. 1-Dodecene	24± 9
5. 3-Buten-2-one, 4-phenyl-	24± 9
6. Dihydroactinidolide	26± 10
<b>Site 2 untreated bottom ash</b>	
1. Pyrrolidine, 2-ethyl-1-methyl-	8± 3
2. Benzaldehyde	4± 1
3. Hexanoic acid	10± 4
4. 1-Hexanol, 2-ethyl-	12± 4
5. Heptanoic acid	6± 2
6. Octanoic Acid	16± 6
7. Benzoic Acid	16± 6
8. n-Decanoic acid	18± 7
9. Vanillin	44± 17
10. Lauric anhydride	10± 4
11. Phenol, 4,4'-(1-methylethylidene)bis- <i>Bisphenol A</i>	28± 11
<b>Site 3 untreated bottom ash</b>	
1. Benzene	3528± 1411
2. Benzaldehyde	174± 69
3. 1-Hexanol, 2-ethyl-	90± 36
4. Dihydroactinidiolide	70± 28

Compound	Semi-quantitative µg/l
<b>Site 1 carbonated bottom ash</b>	
1. Butanoic acid	100± 40
2. Butanoic acid, 3-methyl-	50± 20
3. Butanoic acid, 2-methyl-	38± 15
4. Ethylisoamylketone	234± 93
5. Pentanoic acid, 4-methyl-	60± 24
6. Benzaldehyde	24± 9
7. Hexanoic acid	70± 28
8. 2-Propyl-1-pentanol	24± 9
9. Benzoic Acid	66± 26
10. iso-Vanillin	226± 90
11. Lauric anhydride	50± 20
12. Benzenepropanoic acid	22± 8
<b>Site 2 carbonated bottom ash</b>	
1. Hexanoic acid	58± 23
2. 1-Hexanol, 2-ethyl-	22± 8
3. Heptanoic acid	34± 13
4. Benzoic Acid	120± 48
5. Nonanoic acid	26± 10
6. n-Decanoic acid	106± 42
7. Vanillin	230± 92
8. Lauric anhydride	116± 46
9. Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	22± 8
10. Phenol, 4,4'-(1-methylethylidene)bis- <i>BisPhenol A</i>	80± 32
11. Caffeine	20± 8
<b>Site 3 carbonated bottom ash</b>	
1. Benzene	4182± 1672
2. Butanoic acid	38± 15
3. Butanoic acid, 3-methyl-	36± 14
4. 3-Heptanone, 5-methyl-	134± 53
5. Benzaldehyde	82± 32
6. Heptanoic acid	50± 20
7. Octanoic Acid	142± 56
8. Benzoic Acid	130± 52

**Site 2 carbonated bottom ash (continued)**

9. Benzeneacetic acid	50± 20
10. Nonanoic acid	66± 26
11. Benzylmalonic acid	176± 70
12. n-Decanoic acid	182± 72
13. Benzaldehyde, 4-hydroxy-	24± 9
14. iso Vanillin	484± 193
15. Aceto vanilone	22± 8
16. Butyl maleate	26± 10
17. Dihydroactinidiolide	44± 17
18. Lauric anhydride	136± 54
19. Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	32± 12
20. Tetradecanoic acid	22± 8
21. Caffeine	34± 13
22. 5,10-Diethoxy-2,3,7,8-tetrahydro-1H,6H-dipyrrolo[1,2-a;1',2'-d]pyrazine	36± 14
23. Methyl Linoleate	114± 45
24. Bisphenol A	170± 68

Compound	Semi-quantitative µg/l
<b>Site 1 untreated APC residue</b>	
1. Ethylisoamylketone	78± 31
2. 1-Hexanol, 2-ethyl-	44± 17
<b>Site 2 untreated APC residue</b>	
1. 1-Hexanol, 2-ethyl-	22± 8
<b>Site 3 untreated APC residue</b>	
1. 3-Heptanone, 5-methyl-	138± 55

Compound	Semi-quantitative µg/l
<b>Site 1 carbonated APC residue</b>	
1. Ethylisoamylketone	114± 45

<b>Site 2 carbonated APC residue</b>	
1. 3-Heptanone, 5-methyl-	134± 53
2. 1-Dodecene	24± 9

<b>Site 3 carbonated APC residue</b>	
1. 3-Heptanone, 5-methyl-	128± 51

# Appendix K: List 1 trace organics in LS 10 acid leaching eluates

Results of a screening technique conducted by the EA  
National Laboratory Service

All results are given in  $\mu\text{g/l}$  in the eluate as submitted to the  
laboratory



Compound	Semi-quantitative µg/l
<b>Site 1 bottom ash</b>	
1. 3-Heptanone, 5-methyl-	6± 2
2. Benzaldehyde	4± 1
3. Hexanoic acid	4± 1
4. Benzoic Acid	6± 2
5. Vanillin	26± 10
6. 9,12,15-Octadecatrienoic acid, methyl ester, (Z,Z,Z)-	4± 1

<b>Site 2 bottom ash</b>	
1. 3-Heptanone, 5-methyl-	6± 2
2. Hexanoic acid	10± 4
3. 1-Hexanol, 2-ethyl-	10± 4
4. Heptanoic acid	4± 1
5. Octanoic Acid	10± 4
6. Benzoic Acid	26± 10
7. n-Decanoic acid	18± 7
8. Vanillin (4-Hydroxy 3-Methoxy Benzaldehyde)	48± 19
9. Ethanone, 1-(4-hydroxy-3-methoxyphenyl)-	4± 1
10. Dodecanoic acid	18± 7
11. Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	4± 1
12. 1,2-Benzenedicarboxylic acid, bis(2-methylpropyl) ester	4± 1
13. Caffeine	10± 4
14. Hexadecenoic acid, Z-11-	4± 1
15. n-Hexadecanoic acid	4± 1
16. 5,10-Diethoxy-2,3,7,8-tetrahydro-1H,6H-dipyrrolo[1,2-a;1',2'-d]pyrazine	6± 2
17. 9,12-Octadecadienoic acid (Z,Z)-	6± 2
18. Phenol, 4,4'-(1-methylethylidene)bis- <i>Bisphenol A</i>	18± 7

Compound	Semi-quantitative µg/l
<b>Site 3 bottom ash</b>	
1. 3-Heptanone, 5-methyl-	10± 4
2. 1-Hexanol, 2-ethyl-	12± 4
3. 2,5-Furandione, 3,4-dimethyl- (Dimethyl Maleic anhydride)	8± 3
4. Phenol, 2-nitro-	4± 1
5. Propanedioic acid, phenyl- (Phenyl Malonic Acid)	8± 3
6. Benzylmalonic acid	28± 11
7. 2-Butenedioic acid (Z)-, dibutyl ester	6± 2
8. 2(4H)-Benzofuranone, 5,6,7,7a-tetrahydro-4,4,7a-trimethyl-	8± 3
9. Tetrahydrofuran-2-one, 5-[1-hydroxyhexyl]-	10± 4
10. Benzaldehyde, 4-hydroxy-3-methoxy-5-nitro- (Nitro-Vanilin)	2± 0
11. 2-Hydroxy-3,5-dinitroanisole	52± 20
12. Caffeine	2± 0

Compound	Semi-quantitative µg/l
<b>Site 1 APC residue</b>	
1. 3-Heptanone, 5-methyl-	5±1
2. 2-Propyl-1-pentanol (Hexanol-2-Ethyl)	6±2
<b>Site 2 APC residue</b>	
1. 3-Heptanone, 5-methyl-	16± 6
2. 1-Hexanol, 2-ethyl-	8± 3
3. Methyl formate	8± 3
<b>Site 3 APC residue</b>	
1. 2-Hexanol, (R)-	4± 1
2. 3-Heptanone, 5-methyl-	22± 8

# Appendix L: List 1 trace organics in column leaching test eluates

Results of a screening technique conducted by the EA  
National Laboratory Service

All results are given in  $\mu\text{g/l}$  in the eluate as submitted to the  
laboratory

Compound	Semi-quantitative µg/l
<b>Site 1 untreated bottom ash</b>	
1. Cyclohexanone	698± 279
2. Benzaldehyde	34± 13
3. 1-Hexanol, 2-ethyl-	166± 66
4. Cyclohexanone, 3,3,5-trimethyl-	54± 21
5. Benzyl Alcohol	18± 7
6. 2-Cyclohexen-1-one, 3,5,5-trimethyl-	4± 1
7. 2(4H)-Benzofuranone, 5,6,7,7a-tetrahydro-4,4,7a-trimethyl-	42± 16
8. 4-Methyl-N-(2-oxobutyl)benzenesulfonamide	10± 4
9. 5,10-Diethoxy-2,3,7,8-tetrahydro-1H,6H-dipyrrolo[1,2-a;1',2'-d]pyrazine	14± 5
<b>Site 2 untreated bottom ash</b>	
1. Hexanal	6± 2
2. Butanoic acid, 3-methyl-	6± 2
3. Cyclohexanone	862± 344
4. Benzaldehyde	14± 5
5. Phenol	4± 1
6. Hexanoic acid	48± 19
7. 1-Hexanol, 2-ethyl-	114± 45
8. Cyclohexanone, 3,3,5-trimethyl-	26± 10
9. Heptanoic acid	16± 6
10. Hexanoic acid, 2-ethyl-	10± 4
11. 2-Cyclohexen-1-one, 3,5,5-trimethyl-	4± 1
12. Octanoic Acid	74± 29
13. Benzoic Acid	12± 4
14. 1,4:3,6-Dianhydro-α-d-glucopyranose	6± 2
15. Nonanoic acid	10± 4
16. Caprolactam	6± 2
17. n-Decanoic acid	44± 17
18. Benzaldehyde, 4-hydroxy-	38± 15
19. Vanillin (4-Hydroxy 3-Methoxy Benzaldehyde)	496± 198
20. Ethanone, 1-(4-hydroxy-3-methoxyphenyl)- <i>Acetoguaiacon</i>	24± 9
21. 2(4H)-Benzofuranone, 5,6,7,7a-tetrahydro-4,4,7a-trimethyl-	14± 5
22. Benzenesulfonamide, 4-methyl-	24± 9
23. 3,5-di-tert-Butyl-4-hydroxybenzaldehyde	4± 1
24. 5,10-Diethoxy-2,3,7,8-tetrahydro-1H,6H-dipyrrolo[1,2-a;1',2'-d]pyrazine	22± 8
25. 1-Naphthalenepropanol, α-ethenyldecahydro-α,5,5,8a-tetramethyl-2-methylene-, [1S-[1α(R*),4α,8α]]- <i>Epimanol</i>	16± 6

Compound	Semi-quantitative ug/l
<b>Site 2 carbonated bottom ash</b>	
1. 3-Heptanone, 6-methyl-	156± 62
2. 1-Hexanol, 2-ethyl-	30± 12
3. Cyclohexanone, 3,3,5-trimethyl-	84± 33
4. Hexanoic acid, 3,5,5-trimethyl-	6± 2
5. Caprolactam	12± 4
6. Cyclopentanone, 2,4,4-trimethyl-	8± 3
7. 2-Butenedioic acid (Z)-, dibutyl ester <i>Dibutyl Maleate</i>	40± 16
8. Benzenesulfonamide, 4-methyl-	16± 6

Compound	Semi-quantitative ug/l
<b>Site 1 untreated APC residue</b>	
1. 2-Pentanone, 4-hydroxy-4-methyl- <i>Diacetone</i>	8± 3
2. Cyclohexanone	84± 33
3. 3-Heptanone, 5-methyl-	12± 4
4. 1-Hexanol, 2-ethyl-	6± 2
5. Cyclohexanone, 3,3,5-trimethyl-	4± 1
<b>Site 1 carbonated APC residue</b>	
1. Hexanedioic acid, bis(2-ethylhexyl) ester	34± 13

Compound	Semi-quantitative ug/l
<b>Site 2 untreated APC residue</b>	
1. 2-Pentanone, 4-hydroxy-4-methyl- <i>Diacetone</i>	8± 3
2. 3-Octanone	40± 16
3. 1-Hexanol, 2-ethyl-	12± 4
4. Diisooctyl adipate	158± 63

We welcome views from our users, stakeholders and the public, including comments about the content and presentation of this report. If you are happy with our service, please tell us about it. It helps us to identify good practice and rewards our staff. If you are unhappy with our service, please let us know how we can improve it.