

NUTEK-FBT--96-3

SE9607498



SE9607498

**Characterization of residues from waste combustion in
fluidized bed boilers
Evaluation report**

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Pär Elander

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Titel: Characterization of residues from waste combustion in fluidized bed boilers. Evaluation report.

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RAPPORT INOM OMRÅDET FÖRBRÄNNING/FÖRGASNING

Rapportnummer: FBT-96/3

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Projektnummer: P3740-1

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**SWEDISH NATIONAL BOARD FOR
INDUSTRIAL AND TECHNICAL DEVELOPMENT**

**Characterization of residues
from waste combustion
in fluidized bed boilers**

EVALUATION REPORT

**Kvaerner EnviroPower AB
Swedish Geotechnical institute**

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SUMMARY

In this report a thorough characterization of the solid residues from municipal solid waste combustion in a Kvaerner EnviroPower bubbling fluidized bed boiler (BFB) in Lidköping, Sweden, is presented. Three different end products are generated, namely bottom ash, cyclone ash and filter ash. The bottom ash, consisting of bed ash and hopper ash, is screened and useful bed material recycled. In the characterization, also the primary constituents bed ash and hopper ash have been included.

A chemical characterization have been performed including total inorganic contents, content of unburned matter, leaching behaviour (availability tests, column tests, pH-static tests) and leaching tests according to certain standards for classification (AFX31-210, DIN38414, TCLP).

Physical characterization have included grain size distribution, grain density, compaction properties and stabilisation of cyclone ash with subsequent testing of compressive strength and saturated hydraulic conductivity.

The residues from fluidized bed combustion are finer grained than traditional grate residues. With respect to the grain size distribution, the bottom ash and the bed ash can be characterized as a gravelly sand, hopper ash as sand, cyclone as a sandy loam and filter ash as a silt. The bottom ash is medium graded while the other residues are uniformly graded.

The content of unburned matter in the investigated ashes is very low. The highest content of unburned matter was detected in the cyclone ash with 0.2-0.3 %. For the other ash types the content unburned matter was lower than 0.1 %. Total inorganic contents in the ashes were similar to traditional grate residues (Swedish data) with some exceptions. The content of silicon was higher in the bottom ash from Lidköping, possibly due to the bed material (sand), while the calcium content was lower. The trace element contents were mostly within the range measured for corresponding grate residues. However, the distribution of lead was different, with a lower concentration in the bottom ash and a higher concentration in the filter ash. Also for copper a higher concentration was noticed in the filter ash.

The bottom, bed, hopper and cyclone ashes are principally comparable to bottom ashes from mass burn incinerators also with respect to the leaching behaviour (availability for leaching as well as release with time) of trace elements. In column tests, the measured release from these ashes were in the lower part of the interval reported for bottom ashes from mass burn incinerators (International Ash Working Group 1995). This is valid for Cd, Cu, Ni, Pb and Zn. For Cr, the release was in the middle of the interval. For As, the results indicate that the release from the cyclone and hopper ashes were higher than is reported for bottom ashes from mass burn incinerators. However, the release still was rather limited.

The measured leaching behaviour of filter ash is similar to the leaching behaviour for other APC (Air Pollution Control) residues from incineration of municipal solid waste with a high release of salts and trace elements, probably representing soluble chemical species at the actual pH controlled by the residue.

The leaching tests indicate that handling and disposal of bottom and cyclone ash should not constitute any particular problem from the environmental point of view although the landfill

classification varies between different countries according to varying test methods and different sets of limits.

On the other hand, disposal of filter ash probably will constitute a problem from the environmental point of view. The filter ash is comparable to other dry and semidry APC (Air Pollution Control) residues from MSWI and the leaching of salts, as well as of trace elements, is considerable. This implies that a qualified landfill is required for disposal. An alternative is treatment of the ash prior to landfilling, either by washing or by stabilization/solidification, in order to reduce the leaching. For some countries limits for disposal is exceeded by the filter ash and treatment thus should be necessary.

From an environmental point of view, the quality of the bottom ash and probably the cyclone ash from fluidized bed combustion as determined in this study, indicate a potential for utilization. Utilization of the bottom ash could be accepted in certain countries, e.g. France, according to their current limit values. In other countries, e.g. Sweden, no general limit values are given and utilization have to be applied for in each case. The judgement is then based, not only on total contents in the residue and its leaching behaviour, but also on the specific environmental conditions at the site.

A possible field for utilization of bottom ash is as fill material. According to the grain size distribution and compaction properties, the bottom ash does not meet Swedish requirements for qualified road construction material such as base course gravel, but can probably be used as replacement for sand and similar natural materials in filling applications. From the technical point of view, it may also be possible to utilize a mixture of the bottom ash and the cyclone ash as fill material.

Tests with stabilization of cyclone ash in order to improve the possibilities for utilization gave different results as measured by the development of compressive strength with time. The results indicate that the chemistry of the hardening reactions have to be further studied before any conclusions can be drawn. Probably there are slow reactions which are negative for the hardening in the longer term even if high strength can be obtained in the short term. One obstacle can be formation of hydrogen gas which can take place when water is added to the cyclone ash and causes swelling. The presence of such reactions imply that a special cement have to be used if a durable stabilization shall be achieved.

Comparisons between different specifications for the use of ashes as binding agents in cement and concrete show that it may be possible to use cyclone ash and hopper ash in such applications. This however needs to be further investigated.

ACKNOWLEDGEMENTS

This work was financially supported by the Swedish National Board for Industrial and Technical Development. The project also enjoyed financial support from Lidköpings Värmeverk AB, Västerviks Värmeverk AB and Bollnäs kommun - Tekniska kontoret, Värmeverksenheten.

We would also like to thank the personnel at Lidköping Värmeverk for all their help and practical support during the test runs.

Finally, thanks are due to the technical advisory committee - Karin Öberg, Helena Bredin, Lars-Erik Hägerstedt, Jan-Eric Isaksson, Klas Olofsson and Cecilia Öhman - for their help and advice.

1. INTRODUCTION

The environmental aspects of the solid residues from waste combustion have moved to the forefront of both research and public concern. The solid residues differ in some respects between different combustion techniques, and it is therefore of great interest to study the characteristics of the residues from the more recently developed techniques for waste combustion as a comparison to the traditional mass burn residues.

Fluidized bed combustion is today a well established environmental friendly technique, which is now being accepted internationally for waste combustion. The advantages are among others a higher combustion efficiency, a greater fuel flexibility and a possibility to co-fire different types of fuels, which is important factors for many waste handling schemes. The solid residues from fluidized bed combustion of municipal solid waste (MSW) are known to show a better burnout than traditional mass burn facilities, and easy handling due to its dry state. The available data on other environmental aspects of fluidized bed combustion residues, as for example heavy metal leachability, is very limited, and a characterization study is therefore motivated.

In this report a thorough characterization of the solid residues from MSW combustion in a Kvaerner EnviroPower bubbling fluidized bed boiler (BFB) in Lidköping, Sweden, is presented. Considerations for handling and disposal, as well as the potential for utilization are discussed. A comparison with existing data for traditional massburn residues is also made.

The investigation has been conducted by the Swedish Geotechnical Institute (SGI), and the residue sampling was carried out by Kvaerner EnviroPower AB.

2. FLUIDIZED BED COMBUSTION TECHNOLOGY

The fluidized bed of sand at the bottom of the furnace in a fluidized bed combustor offers an element of combustion control that does not exist in traditional grate fired boilers. The hot fluidized bed represents a large amount of stored energy, which is used to ignite the fuel and assure a complete combustion, and also to control the heat transfer to the boiler. The bed functions as a "thermal flywheel" keeping a constant temperature and levelling out variations in fuel quality and moisture content.

Together with a good mixing between fuel and air this creates excellent combustion conditions, allowing for a lower combustion temperature and excess air ratio and thereby minimizing the formation of nitrogen oxides.

There are mainly two types of fluidized bed boilers, and they are named according to the level of fluidization of the bed. In the bubbling fluidized bed boilers (BFB's) the velocity of the combustion air coming through the bottom plate distributor is enough to lift and expand the bed, so that it resembles a boiling liquid with bubbles of hot gases travelling through. If the velocities are raised further as in circulating fluidized bed boilers (CFB's) it leads to entrainment of particles up through and out of the furnace. The main part of the particles which are transported out of the furnace are caught in cyclones (or other types of dust separation equipment) and recirculated back to the furnace in a closed loop.

The additional ways, compared with traditional grate fired boilers, of controlling the heat transfer in fluidized bed boilers are through in-bed heat transfer surfaces and air distribution, and for CFB's also external heat exchangers.

A fluidized bed boiler for waste combustion offers:

- possibility to burn a wide range of fuels (from low grade to high calorific fuels) giving a large flexibility for the plant operator
- ability to co-fire different types of fuels - as for example sludge in combination with coal
- high combustion efficiency and ash burnout
- low NO_x emissions
- possibility to add absorbents to the bed for reduction of acid gases.

2.1. Fluidized bed boiler residues

The main difference between fluidized bed combustion residues and traditional incinerator residues are the larger amount of fly ash (particles entrained with the flue gas stream) for the fluidized bed case due to the higher gas velocities used in the furnace. The bottom ash from fluidized bed boilers represents about 20 - 50% (depending on the waste fuel and degree of processing) of the total ash flow, and the rest leaves the furnace as fly ash. Most of the fly ash can be collected by dust separators before the flue gas cleaning system. In traditional incinerators the bottom ash constitutes about 80-90% of the total residues.

Thanks to the mechanical forces in the bed and the fuel processing the residues are also finer grained than traditional grate residues. This is of course one of the reasons for the better burn-out of the fuel, and the larger fly ash flow.

3. THE LIDKÖPING BFB PLANT

The Lidköping Waste to Energy Plant is situated on the shores of Lake Vänern in the southwest part of Sweden. The plant incorporates two 15 MWth BFB boilers which burns about 50 000 tonnes of waste fuels annually. 20 000 tonnes are the nearby communities household and commercial waste, and typically one of the boilers fire 100% MSW. The two BFB's have been in operation since 1984, and were both retrofitted in 1994 with a new low emission combustion zone.

The boilers are equipped for power generation, but today only hot water for the district heating net is produced.

The fuel preparation before combustion is simple and flexible. Bulky items are removed at the reception, using a grab crane. Waste is then fed to a hammer mill. This is followed by a magnetic separator, where 85 % of the ferrous metal is removed. Finally, the shredded refuse is fed to a large silo before being fed to the boiler.

The bottom ash (bed and hopper ash) is screened and useful bed material is returned to the furnace. The rest of the material is transported to a bottom ash silo. The cyclone ash and the baghouse filter ash are sent to a common silo for combined fly ash.

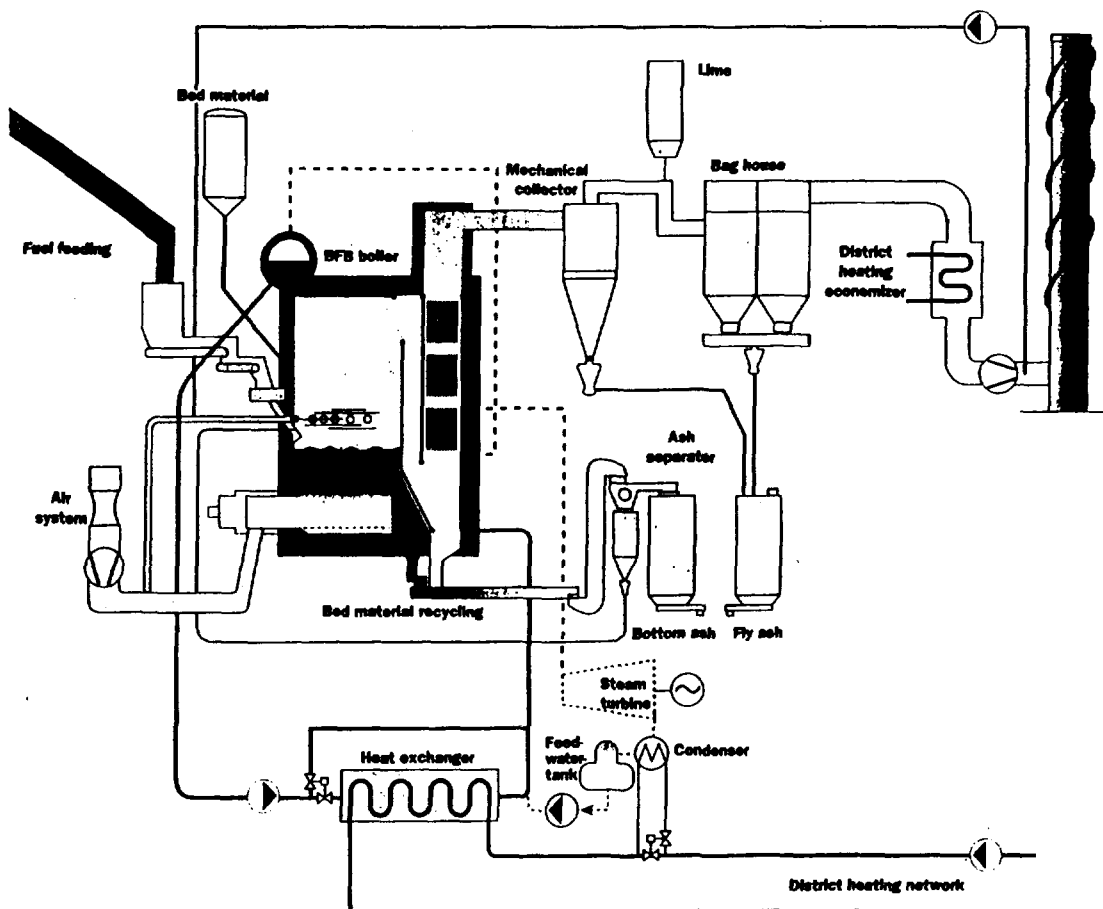


Figure 3.1. Schematic diagram on the Lidköping Waste to Energy Plant.

4. ASH SAMPLING

4.1. Boiler operation during the test runs

The sampling was conducted during a two week period in March 1994. The boiler was operated in two operational modes, a full load case and a low load case (60 % load) during that period. The operational mode for each day were selected randomly.

The excess air was about 45% (slightly higher for the low load case), and the fluidized bed temperature was in the range 780 - 825 °C. The emissions to the atmosphere during the test runs was, with a few borderline exceptions for HCl, well below the existing EU regulations for new municipal waste incineration plants.

Only 100% MSW was fired during the sampling period. The MSW fuel had the following composition:

- 46.6 % waste direct from households
- 26.4 % sorted waste (household and light industry, burnable fraction)
- 16,2 % business waste (mainly paper and plastics from packaging)
- 10.8% RDF (well sorted householdwaste)

A rough average chemical composition (four samples from four testdays - each consisting of eight subsamples taken from the fuel conveyor band) is as follows:

Moisture, % 35.8

On dry sample (in %):

Ash	16.5
C	47.9
H	6.8
O	27.4
N	0.85
S	0.15

NCVwet, MJ/kg 11.5

4.2. Sampling method

All four primary outgoing flows of residues from the plant (bed ash, hopper ash, cyclone ash and filter ash) were sampled, although some useful bed material is recovered afterwards and the rest of the material is combined to only two residue types at the Lidköping plant. This was done in order to assure that representative samples from the test periods were taken, and since the residues can be handled in other ways at new installations.

Every sampling period was preceded by an at least 10 hour long stabilization period with the selected operational mode. After the stabilization period an eight hour long sampling period started. During each sampling period eight incremental samples of every residue stream were taken at a random time once every hour. One incremental sample every hour was judged to be sufficient since there are no important process variations with a higher frequency. Other factors affecting the necessary number and size of incremental samples are:

- the total amount of material from which samples are taken
- the size distribution of the material
- the expected variation between the samples

The total amounts in the residue flows during the sampling period were relatively small, and according to the dutch proposal NVN 5860 *Sampling of Waste* only four incremental samples would be necessary. The IAWG suggests 24 incremental samples for massburn bottom ash and a lower number (no recommendation is given) for other types of ashes. The expected variation between the bottom ash samples from a fluidized bed boiler is lower than for massburn bottom ash, since the ash is well mixed in the bed, and therefore eight incremental samples was considered enough for all ashes. The size (weight) of the incremental samples should according to a proposed Swedish Standard (source: SGI Varia 413) be at least

$M(\text{kg})=0,1 \cdot D(\text{mm})$ - but minimum 0,5 kg

which would mean about 2 kg bottom ash, and 0,5 kg of boiler ash, cyclone ash and filter ash each. In the proposed dutch standard NVN 5860 *Sampling of Waste* a minimum amount of 1 dm³ is suggested. For all four types of ashes these requirements were met in the sampling as can be seen below:

The sampling was done in falling stream for all four residue types. The bottom ash and boiler ash were sampled at the ash drainage systems beneath the furnace and below the furnace back pass hopper respectively. About 4 dm³ (about 5-6 kg bottom ash and 4-5 kg boiler ash) was collected and saved as the incremental sample.

The baghouse filter ash and cyclone ash were both sampled from pneumatic conveyor vessels. The collected amounts of ash (about 10-40 dm³) was divided down through sample splitting to about 4 dm³ (3-4 kg cyclone ash and 1-2 kg filter ash) which was saved as the incremental sample.

The eight incremental samples for each residue type were mixed together to form a general sample for that day, operational mode, and residue type. A volume of 16 dm³ of the general sample for each residue type was put in air tight plastic containers and saved for analysis.

From the general samples of bed and hopper ash a mixture similar to the resulting bottom ash at the plant was obtained through sieving and mixing, and used in the study.

5. INVESTIGATIONS

5.1. Scope

Extensive chemical and physical characterization have been carried out on the primary residues from the plant i. e. bed ash, hopper ash, cyclone ash and filter ash. In order to clarify possible effects of the mixing of coarse bed ash and hopper ash that results in the bottom ash, and possible divergent properties of the residue compared to the primary ash products, a the week sample from the bed ash was sieved and the coarse fraction mixed with the hopper ash according to the procedures in the plant. Chemical and physical characterization was carried out also on the bottom ash but to a somewhat less extent.

The possible effects on the residues from the boiler operational mode was also investigated i. e. chemical characterisation were performed on residues from the low load case as well as from the full load case.

5.1.1. Chemical characterization

The chemical characterization comprised the following analyses for the different cases:

Day samples (individual samples) full load and low load conditions:

- ★ Total content (only primary samples)

Week samples (gross samples) full load conditions:

- ★ Total content
- ★ Content unburned matter
- ★ Column leaching test (only primary samples)
- ★ CEN leaching test (L/S¹=2 and L/S=10, accumulated)
- ★ pH-constant leaching test

¹L/S denotes the weight relation between the liquid phase (L) and the solid phase (S) in a leaching test.

- ★ Availability test
- ★ TCLP leaching test (U.S.A)
- ★ AFX31-210 leaching test (France)
- ★ DIN38414 leaching test (Germany)

Week samples (gross samples) low load conditions (only primary samples):

- ★ Total content
- ★ Availability test
- ★ CEN leaching test (L/S¹=2 and L/S=10, accumulated)
- ★ Content unburned matter

5.1.2. Physical characterization

The physical characterization comprised the following analyses:

Week samples (gross samples) full load and low load conditions:

- ★ Grain density (only primary samples)
- ★ Grain size distribution
- ★ Proctor compaction tests

Week samples (gross samples) full load conditions - cyclone ash:

- ★ Stabilization with cement - determination of uniaxial shear strength after 7, 14, and 28 days of curing, and permeability after 28 days of curing.

5.2. Experimental

5.2.1. Chemical characterization

Total analysis (solid material)

The ashes were dried at 105 °C according to Swedish standard SS 028113. The samples were put in teflon caps, concentrated HNO₃ and water (1/1) was added and the caps were sealed. Analysis of As, Cd, Cu, Co, Hg, Ni, Pb, and Zn was done according to modified EPA-methods 200.7 and 200.8.

For the analysis of other elements Si, Al, Ca, Fe, K, Mg, Mn, Na, P, Ti, Ba, Be, Cr, La, Mo, Nb, S, Sb, Sc, Sn, Sr, V, W, Y, Yb, Zr 0,125 g of sample was melted with LiBO₂ and dissolved in HNO₃. Se was also determined in the full load case. Determination of element concentrations were made with ICP-AES and ICP-MS. The determinations were performed by SGAB in Luleå, Sweden.

The content of unburnt matter in the ashes were determined by SP in Borås, Sweden, using elementary analysis for determination of total carbon content and loss on ignition in combination with measurement of the loss of CO₂.

Leaching procedures

The ashes were leached under different conditions according to different standard methods. The applied methods and their respective object are as follows:

- *Column test*: The object of this method is to imitate the conditions that are probable to arise in a landfill (or structural fill).
- *pH-static tests*: Leaching are performed as batch tests with a leachate to solid ratio $L/S = 5$ at different pH (adjusted throughout the test) in order to clarify the effect on leaching behaviour of possible change of pH.
- *Availability test*: The object is to obtain what the maximum leachable amount is from a residue independent of pH, grain size and concentration conditions. The sample is ground ($<0,125$ mm) and leaching is performed in two steps (pH 4 and 7) with large quantities of leachant (L/S 100 in each step).
- *CEN-test*: A test method proposed to constitute one of three European standard methods. Leaching is performed as a batch test in two successive steps, the first with a leachate to solid ratio, $L/S = 2$ and the second with leachate up to an accumulated $L/S = 10$.
- *TCLP*: A standard method (batch test with L/S 20 and an adjustment of pH) used in USA for classifications of waste as "hazardous" or "non-hazardous".
- *AFX 31-210*: A standard method used in France for classification of waste. Leaching is carried out as a batch test in three cycles to accumulated L/S 10, 20 and 30 respectively.
- *DIN 38414*: A standard method used in Germany for classification of waste. Leaching is performed as a batch test at L/S 10.

The procedures for the different leaching tests are summarized in Table 5.1 below.

Analysis of leachates

The produced leachates were analysed for pH, redox, conductivity, Cl^- and SO_4^{2-} . From the leachates a portion was withdrawn and acidified to $pH < 2$ with HNO_3 prior to analysis for elements. For all tests, the filtered and acidified leachates were analysed for the following elements: Ca, Fe, K, Mg, Na, S, Si, Al, As, Ba, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Zn. For TCLP leachates also Se was included in the element analyses. All leachates were analysed separately for Cr(VI).

The above analysis was completed with different analyses according to the leaching test method according to the following:

- AFX: Cyanide free, Cyanide tot. TOC, COD_{Cr} , Phenol, TDS.
- CEN: HCO_3^- .
- Column: HCO_3^- .
- DIN: F^- , AOX, Phenol, Cyanide, NH_4^+ , TOC, NO_2^- , TDS, conductivity.

Table 5.1. Specifications for leaching tests.

Test	Column	pH static	Availability test	CEN	TCLP	AFX	DIN
Particle size	< 10 mm	< 4 mm	<125µm	< 4 mm	< 9.5 mm	< 4 mm	< 10 mm
Leaching agent	DW at pH4 (HNO ₃)	DW (adj. by 1M HNO ₃)	DW at pH 7 and pH 4 (HNO ₃)	DW	HAc at pH 4.93 or at pH 2.88 ¹⁾	DW	DW
Solid weight	2000 - 7000 g	100 - 150 g	8.0 g	100 - 150 g	100 g	100 g	100 g
Liquid/solid ratio	0 - 2	5 ²⁾	200 ^{2,3)}	2 and 10 ⁴⁾	20	10-30 ⁵⁾	10
Contact time	variable ca 480 h	24 h	3 + 4 h	6 and 18	18 h	16 h	24 h
Mixing	-	stirring	magnetic stirrer	shaking end over end	rotation 30 rpm	shaking end over end	rotation
Filtration	0.45 µm	0.45 µm	0.45 µm	0.45 µm	0.6-0.8 µm	0.45 µm	0.45 µm
Filter type	cellulose acetate	cellulose acetate	cellulose acetate	cellulose acetate	glass fiber filter	cellulose acetate	cellulose acetate

¹⁾ Pretests determine the pH of the leachate. Alkaline samples are leached with the low-pH leachate

²⁾ After required addition of acid

³⁾ Cycles L/S 100 in pH 7 and L/S 100 in pH 4 is put together before filtration

⁴⁾ 2 cycles L/S 0-2 and L/S 2-10 analysed separately

⁵⁾ 3 cycles L/S 0-10, 10-20, and 20-30 analysed separately

DW = Demineralized water

Analysing methods

Analysis on leachates was performed on ICP-AES and ICP-MS for elements. Other analyses were performed according to standard methods as follows:

<u>Parameter</u>	<u>Applied method</u>
Cl ⁻ :	SS 028236/1
SO ₄ ²⁻ :	TRAACS (autoanalyzer)
Cr(VI):	ST M 3500-Cr-1992
pH:	SS028122
Conductivity:	SIS 028123
TOC:	SS028199/1
TDS:	SS028113/1
HCO ₃ ⁻ :	SS028139/1
F ⁻ :	SS028135/1
AOX:	SS028104/1
Phenol:	SS028128/1
Cyanide:	TIM 315-74W
NH ₄ ⁺ :	TRAACS
NO ₂ ⁻ :	TRAACS

Analyses for elements on ICP were performed by SGAB in Luleå, Sweden. The other analyses were performed by KM Laboratories in Linköping, Sweden.

5.2.2. Physical characterization

The test methods used for the physical characterization follow Swedish Standard (SS) and/or recommendations given by the Laboratory Committee of the Swedish Geotechnical Society (SGF). Permeability tests however, were performed in triaxial cells according to an internal SGI-standard described in the Nordtest NT Techn Report 254. The following standards/recommendations have been applied for physical characterization:

Determination of grain density:	SS 02 71 15 - <i>Geotechnical tests - Grain density and specific gravity.</i>
Determination of grain size distribution:	SS 02 71 23 - <i>Geotechnical tests - Particle size distribution - Sieving.</i>
Determination of maximum density:	SS 02 71 09 - <i>Geotechnical tests - Compaction properties - Laboratory compaction.</i>
Determination of strength of stabilized samples:	SS 02 71 28 - <i>Geotechnical tests - Shear strength - Unconfined compression test - Cohesive soil.</i>
Determination of permeability of stabilized samples:	<i>SGI Doc 15 - Internal standard for determination of permeability in triaxial cell</i>

In addition, the grain size distribution for particles smaller than 0.063 mm was carried out by means of laser granulometry.

6. RESULTS

6.1. Total contents

6.1.1. Main constituents

The dominating substances in the ashes are compounds with Si, Al, Ca, and to a lesser extent Na, K, Mg and Fe (Table 6.1). In the filter ashes, the concentrations of Ca is markedly higher than in other fractions. Sulphur is enriched in the filter ashes where it is the fourth most important element. Iron and also Mn belong to a group of element which are found with the highest concentrations in the hopper and cyclone ashes.

The content of unburned matter is generally low and independent of load conditions. This may be of importance for the form in which metals exist (e.g. for Cu and Cr).

Table 6.1. Total concentrations (mg/kg) in ashes (gross samples, full load)

Element	Content in:				
	Bottom ash mg/kg	Bed ash ¹⁾ mg/kg	Hopper ash ¹⁾ mg/kg	Cyclone ash mg/kg	Filter ash mg/kg
Si	303 000	327 000	301 000	200 000	32 700
Al	63 500	52 300	70 100	119 000	22 200
Ca	55 000	43 300	54 900	120 000	363 000
Na	34 900	37 500	25 500	25 400	13 200
Fe	30 500	21 000	34 400	33 900	5 600
K	21 300	24 900	19 800	17 200	8 400
Mg	11 800	6 200	7 800	16 400	10 100
Unburned matter ²⁾	0.09	<0.1	0.08	0.3	0.02
Unburned matter ³⁾	-	<0.1	<0.1	0.22	0.07

¹⁾ No end products

²⁾ Full load conditions

³⁾ Low load conditions

6.1.2. Trace elements

The distribution of some important trace elements in the different ashes are shown in Table 6.2 below.

Table 6.2. Total concentrations in ashes (gross samples, full load)

Ash	As	Cd	Co	Cr	Cu	Hg	Ni	V	Se	Zn
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Bottom	49	7.1	26	350	3000	1.4	160	36	-	3180
Bed ¹⁾	31	1.2	13	357	1800	<0.3	67	25	1.4	1450
Hopper ¹⁾	29	6.4	19	280	3200	<0.3	88	44	1.9	2800
Cyclone	46	9.5	34	410	3200	<0.3	120	54	4.4	6000
Filter	83	89	19	190	5400	2.8	32	14	12	5800

¹⁾ No end product

For several of the trace elements (Pb, Cu, Cd,) most of the content is found in the filter ash. Nearly the same degree of enrichment is true also for As while Zn has the highest amounts in filter and cyclone ash. The contents of certain elements (Hg, Cd, As, Pb, Ni) are higher in the bottom ash than in the primary bed and hopper ashes. This indicate that the screening for recycling of bed material lead to an enrichment in the bottom ash. The concentrations of Hg is generally low (below detection limit) except in the bottom and filter ashes.

6.1.3. Comparisons with other media

The concentrations of trace elements (Table 6.2) can be compared to other sets of data. In a previous study (Ek, 1987) different strata of soils was sampled in an investigation of materials from geochemical reference stations (Table 6.3)

Table 6.3. Median values of soil samples (gross) from 23 stations in Sweden. (A₂ refers to the upper leached soil, B to the enrichment layer beneath A₂ and C to the soil below the enrichment layer)

Type	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	V	Se	Zn
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
A ₂	1.7	0.06	<1	10	12	0.008	3.5	16.5	14.5	0.074	9
B	1.94	<0.06	3	14.5	14	0.025	8	16	28.5	0.31	36.5
C	1.76	<0.06	5	15.5	21.5	0.006	11	13	28.5	0.066	27.5

A comparison shows that the concentrations in the ashes are higher for most elements. For the elements Cd, Cu, Hg, Pb and Zn the concentrations found in the ashes are approximately two orders of magnitude higher than in the soil. For As, Co, Cr, Ni and Se the concentrations are about one magnitude higher, while for V the concentrations are similar. The amounts in the soil are calculated based on dry samples, and not on samples where the organic matter is combusted, meaning that no strong conclusions can be drawn from this material.

Another possibility in assessing the potential hazardous effects of the ashes on basis of their total content of metals can be done from comparisons with sediments. A classification in 5 classes describing environmental effect of metals (Swedish Environmental Protection Agency 1991) have been published. Table 6.4 shows the upper limits for class 3 moderately high and class 4 high concentrations.

Table 6.4. Upper limits for the classification of sediments (mg/kg dry weight)

Class	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Class 3	75	2	75	50	0.3	75	100	300
Class 4	250	5	300	150	1	300	400	1000

If ashes were to be classified in the same way, all Cu and Zn data would belong to the highest class (5), Cd, Cr, Hg, Pb would fall into classes 4 and 5 and Ni and As in classes 3 and 4.

Since the content of organic matter is included in an evaluation of sediments, a combustion of the sediments would theoretically increase the amount in the remaining inorganic material. The organic matter is determined through loss on ignition (LOI). In superficial sediments LOI is highly variable (10 - 90 % of the dry weight).

The comparison between natural materials and ashes is a way to rank trace elements in ashes with respect to their enrichment. From the above comparisons it can be concluded that the elements of environmental concern in the ashes primarily are Cd, Cu, Cr, Hg, Pb and Zn.

6.2. Leaching tests

Unless pH is not adjusted according to the test method, all ashes generate leachates with a high pH. The pH remains high throughout the tests despite sometimes high ratios between liquid and solid (L/S). The alkalinity, measured by titration and expressed as the concentration of HCO_3^- , is high in all leachates. It is amounting to 5000 - 11 000 mg/kg for L/S 2 in the column tests. In the CEN-tests the corresponding values at L/S 2 are for bed ash 900, hopper ash 3 500, cyclone ash 4 500 and for the filter ash 28 000. The values are generally higher at L/S 10 and for cyclone ash it amounts to as much as 120 000 mg/kg, more than 25 times the L/S 2 analysis. It is possible that CO_2 from the air has dissolved into the samples during storage.

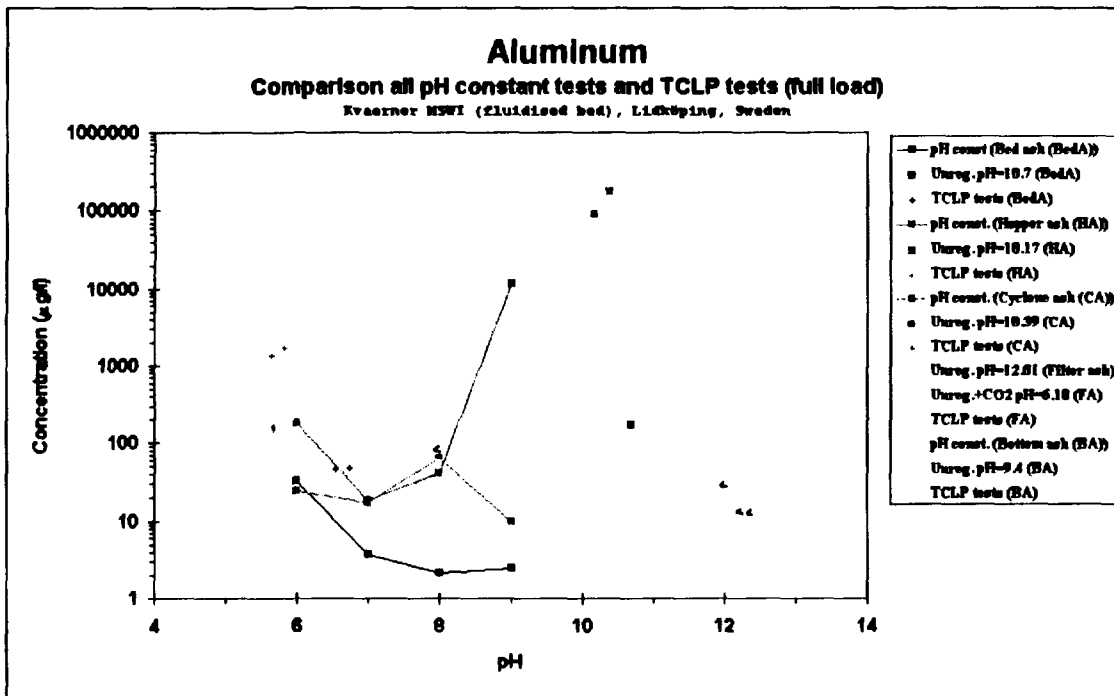
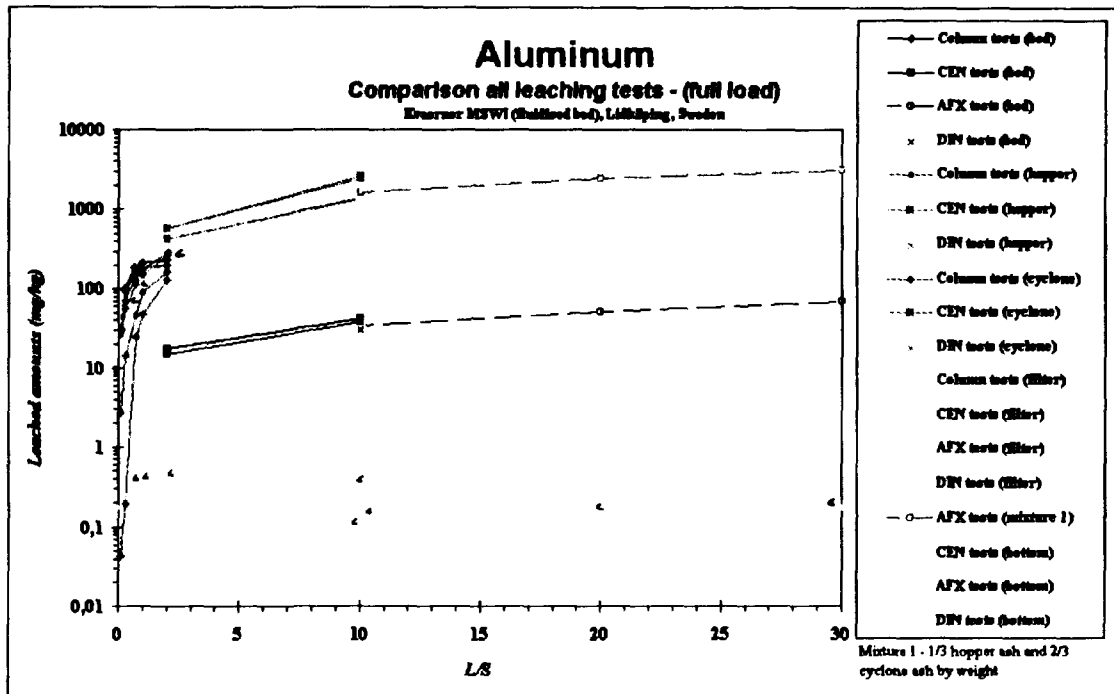
6.2.1. Metals

Aluminium

Only small amounts of the total content of aluminium are available and there is an increasing fraction of the metal that becomes available from bed ash (<1 %) over hopper ash (about 1 %) and cyclone ash (<5 %) to filter ash (<10 %). This can be expected, non-volatile silicates will probably not be affected in the bed ashes. In the filter ashes a larger fraction consists of unconsolidated oxides or hydroxides which are soluble to a higher degree.

For the bed ashes column and availability tests give the same leached amounts despite different conditions for their leaching, about 200 mg/kg (Figure 6.1a). CEN, DIN and AFX give smaller leached amounts. Mechanisms of ion exchange connected to gradients in ionic strength could be the reason for an efficient leaching of Al in the columns for the bed ash. For cyclone and hopper ash the leached amounts in column tests are comparable to the bed ash, whereas leaching in the batch tests (CEN DIN and AFX) give similar or somewhat higher amounts, close to the availability. Leaching from bottom ash is close to the leaching from the primary hopper ash. It can be noticed that the AFX test for the mixture gives an even higher leaching than the availability test does. For the filter ash the leached amounts in all tests in opposite to the other ashes are considerably lower than the available amounts. Also in absolute figures the leaching is lower from the filter ash than from the other ashes.

Aluminium is the dominating element in the bed, hopper and cyclone ashes together with Ca and Si. In spite of that, concentrations are very low in the pH-static test for the bed ash and hopper ash (Figure 6.1b). This is possibly due to the fact that at pH between 6 and 9 Al is found as hydroxides or silicates or adsorbed. The unregulated tests resulted in a pH above 10 where Al predominantly is in the form of $\text{Al}(\text{OH})_4^-$ (aq). This is also probably the reason for the efficient leaching of these ashes in unregulated tests compared to the availability tests and pH-static tests. However, a high concentration in leachate from cyclone ash at pH 9 is noticeable.



Note: Bed ash and hopper ash are no end products
< denotes values below detection limits (shown)

Figure 6.1. Results from leaching tests for Aluminium

Arsenic

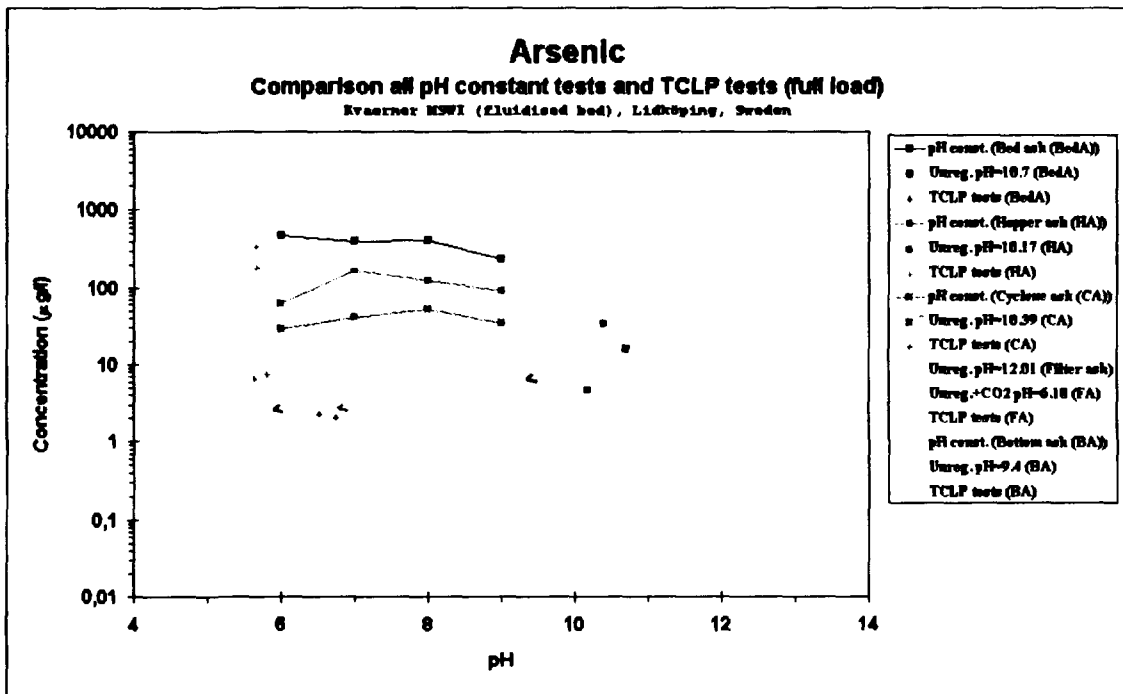
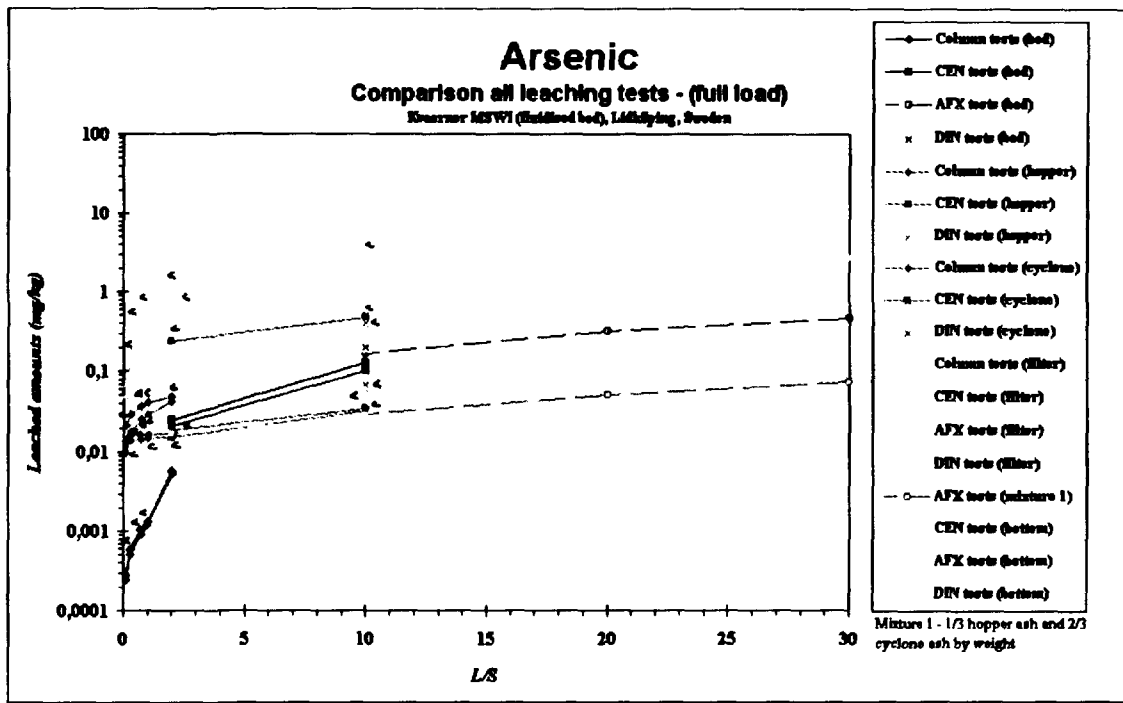
The largest available fraction compared to total content is found in the bed ash, somewhat less than 10 % corresponding to 12 mg/kg. The available fraction for the other ashes, including bottom ash, are 4-6 % or 1 - 10 mg/kg.

Results from different leaching tests are presented in Figure 6.2. There is a substantial difference between availability tests on one hand giving higher results than CEN, DIN and AFX on the other hand. It is no cause to believe that the availability test performed at low pH should give substantially higher values than the leaching tests performed at higher pH for this element, since no clear pH-dependence is found in the pH-static tests (probably because forms mobile in the whole pH-region dominates the leachates: AsO_2^- (aq) or AsO_4^{3-} (aq)). It should thus be the L/S ratio that determines the leachable amounts. In the bottom, bed, hopper and cyclone ashes the availability is about two orders of magnitude higher than the amounts extracted from columns and from batch leaching tests. For filter ash, however, the leaching tests CEN, DIN and AFX are similar to the available fraction. The reason for this phenomena could be absorption of As on hydroxides of Fe in the leaching tests. Since the available Fe is very low in the filter ashes it can be concluded that this form of Fe is not present in the filter ash. It is thus an indication that no amorphous Fe-oxides or hydroxides are present as adsorbents of As in this fraction.

Cadmium

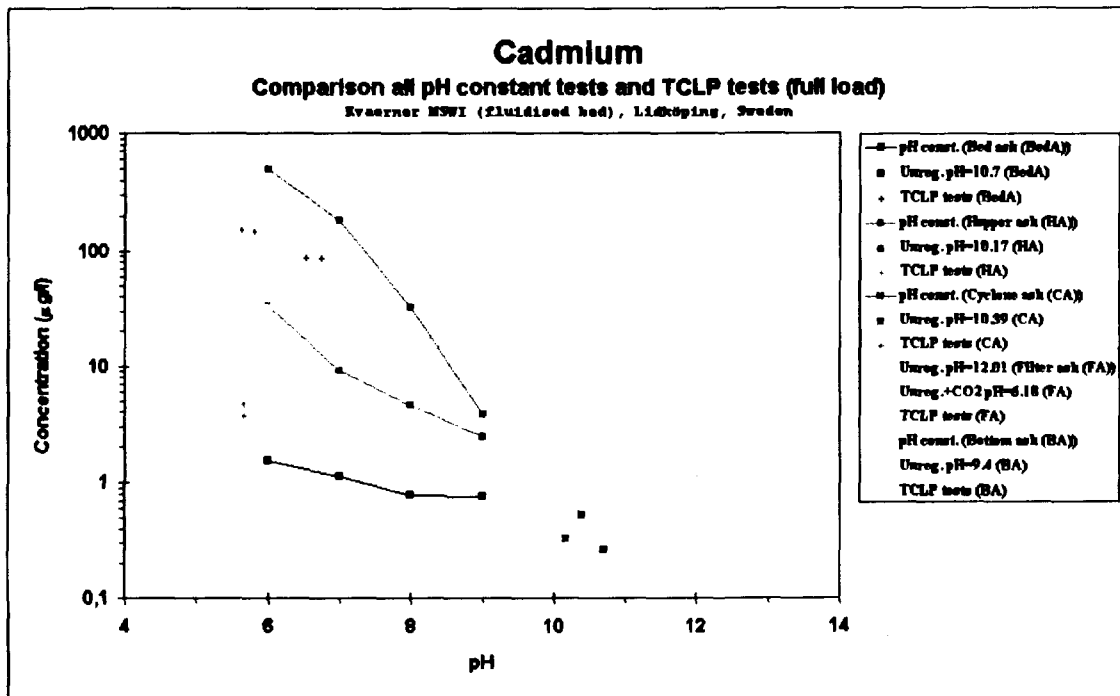
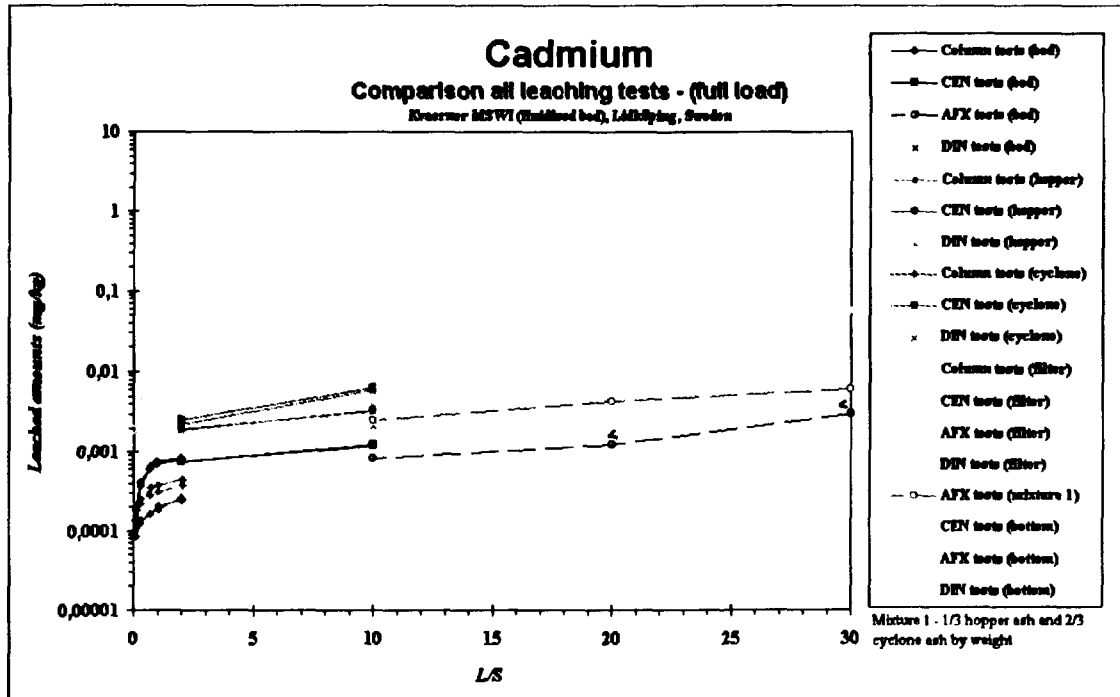
For Cd the available fraction as well as the total amount is increasing from bed ash to filter ash. In the filter ash is about 50 % of the total content available. Consequently, the total concentrations in absolute figures are increasing resulting in available Cd going from 0.1 mg/kg in bed ash via 2-3 mg/kg in hopper and cyclone ashes to 90 mg/kg in filter ash. This is probably caused by the volatility of the element giving higher amounts in the filter ash. For bottom ash leaching is somewhat higher than from hopper ash as well as from bed ash.

The difference between the available fraction and leaching tests are considerable. It generally amounts to between two and three orders of magnitude. The leached amounts in the columns are also considerably lower than in the CEN-tests at similar L/S- ratio except for the bed ashes (Figure 6.3). The pH-dependence on leaching characteristics is evident, since TCLP-tests give similar concentrations as availability tests. The clear dependence on pH with low amounts in the high pH-region is also found in the pH-static tests. In all of the leaching tests it is possible that pH-dependent adsorption (on e.g. CaCO_3) takes place on the solid material. The formation of CdCO_3 (s) is also possible. For bed ashes the release are even higher in the TCLP- tests than the release from the availability test. This could possibly be caused by heterogeneities in the test material. Such effects are more likely in media where the overall concentrations are low, rather than in e.g cyclone or filter ashes.



Note: Bed ash and hopper ash are no end products
 < denotes values below detection limits (shown)

Figure 6.2. Results from leaching tests for Arsenic



Note: Bed ash and hopper ash are no end products
 < denotes values below detection limits (shown)

Figure 6.3. Results from leaching tests for Cadmium

Chromium

Cr can be present in two forms: Cr(III), leachable only at low pH, and Cr(VI), existing in the form of anions. The Cr(VI) is easily leached under the oxidizing conditions, but it will be reduced to the more immobile Cr(III) provided some reducing agent is present (e.g. unburned organic matter). The low content of organic matter could be a reason for the existence of Cr(VI). The Cr(VI) is predominantly found in the bed ash as is found from the leaching tests resulting in higher leached amounts than for hopper and cyclone ashes (Figure 6.4). It should be noticed that Cr(VI) was not detected in bottom ash despite the content of the coarse fraction from the bed ash. Though, because of the high detection limit for this specie, it cannot be concluded that Cr(VI) is not generally present in small amounts in all ashes.

The chemistry of Cr(III) is similar to that for Al(III). The available fraction of Cr is low in relation to total concentrations, comparable with Al. Some differences exist, e.g. the TCLP-results in the hopper ash are much closer to the available fraction for Cr than Al. This could be explained by the different solubilities for the hydroxides at the actual pH of the TCLP-tests. The lowest solubility for $\text{Al}(\text{OH})_{3(s)}$ is at about pH 7 while it is 8,5 for $\text{Cr}(\text{OH})_{3(s)}$. This could on the other hand be an effect of a different oxidation state of Cr as discussed above.

Copper

Copper shows the same pattern as Cd with increasing available fractions from bed ash to filter ash (>50 % of the total content is available in the filter ash)

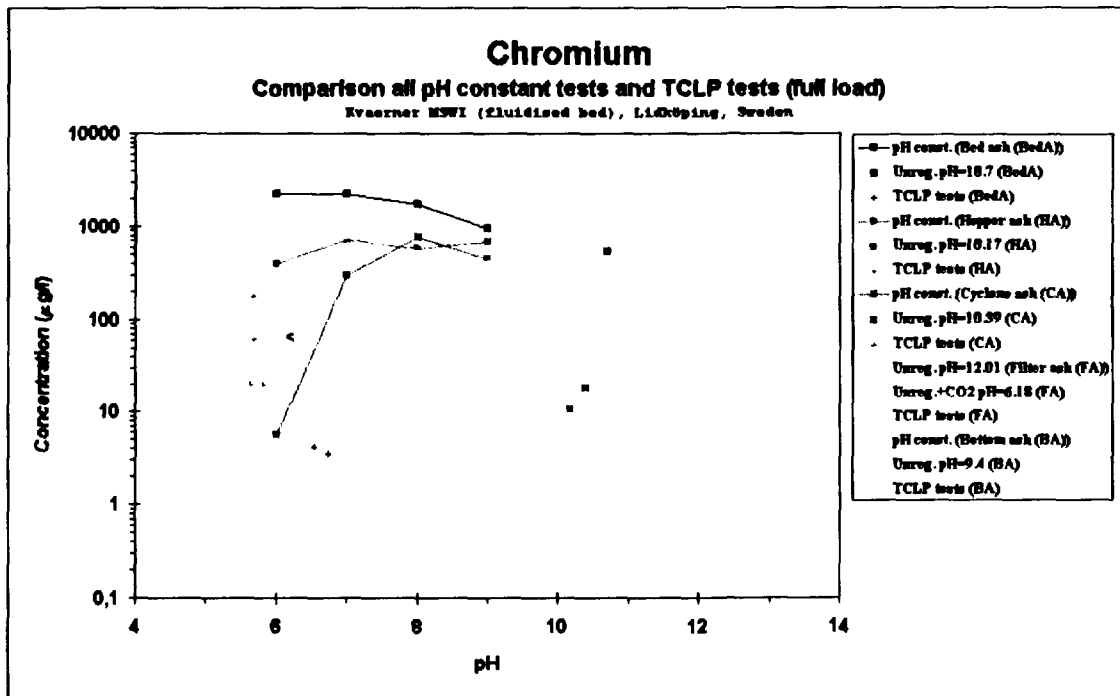
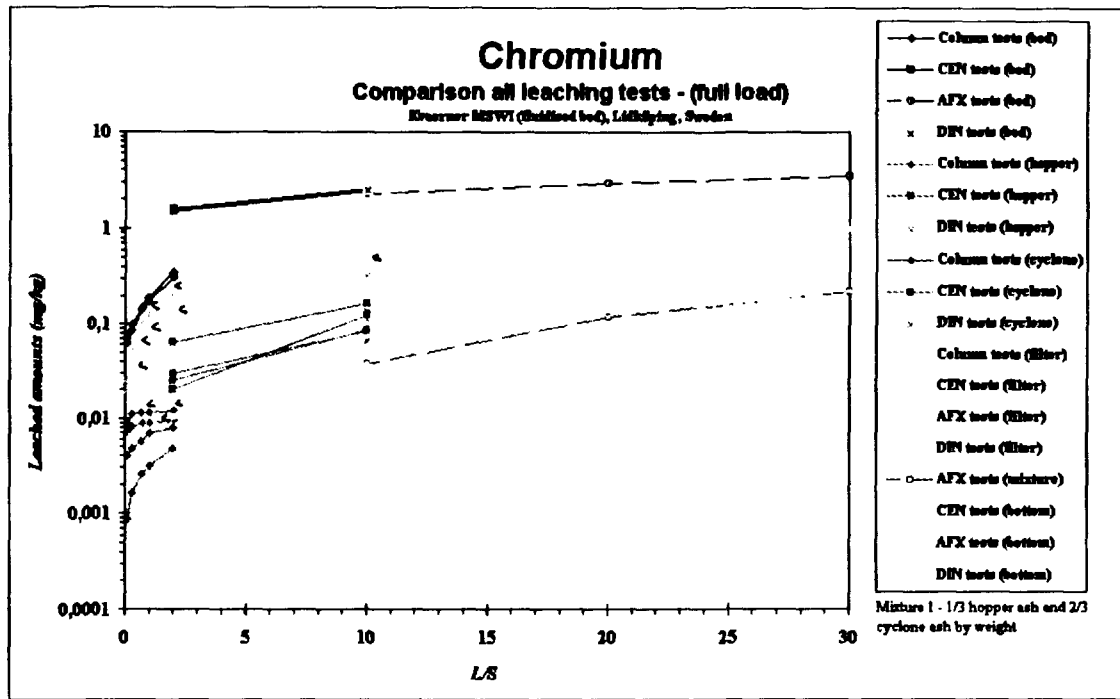
Differences between availability tests and leaching tests are for bottom ash as well as for bed ash about four orders of magnitude. For hopper and cyclone ashes the differences are almost of the same order (3 - 4). This means that for most of the leaching tests CEN, DIN, AFX and column tests the leached amounts are below 0,1 mg/kg (Figure 6.5). The leaching of Cu is very pH-dependent, similar to Cd, reflected by the increased amounts leached in the TCLP-tests and found in the pH-static tests.

For filter ash the situation is different. The difference between availability and batch leaching tests are not that pronounced and concentrations of leached amounts are in these cases between 100 - 1000 mg/kg. There is instead a great difference between column and batch tests (CEN), (Figure 6.5). This could be caused by ion exchange or adsorption to the column material.

Organic complexation is often discussed in connection to Cu leading to increased leaching at intermediate and high pH. There is no evidence of this in the investigated ashes.

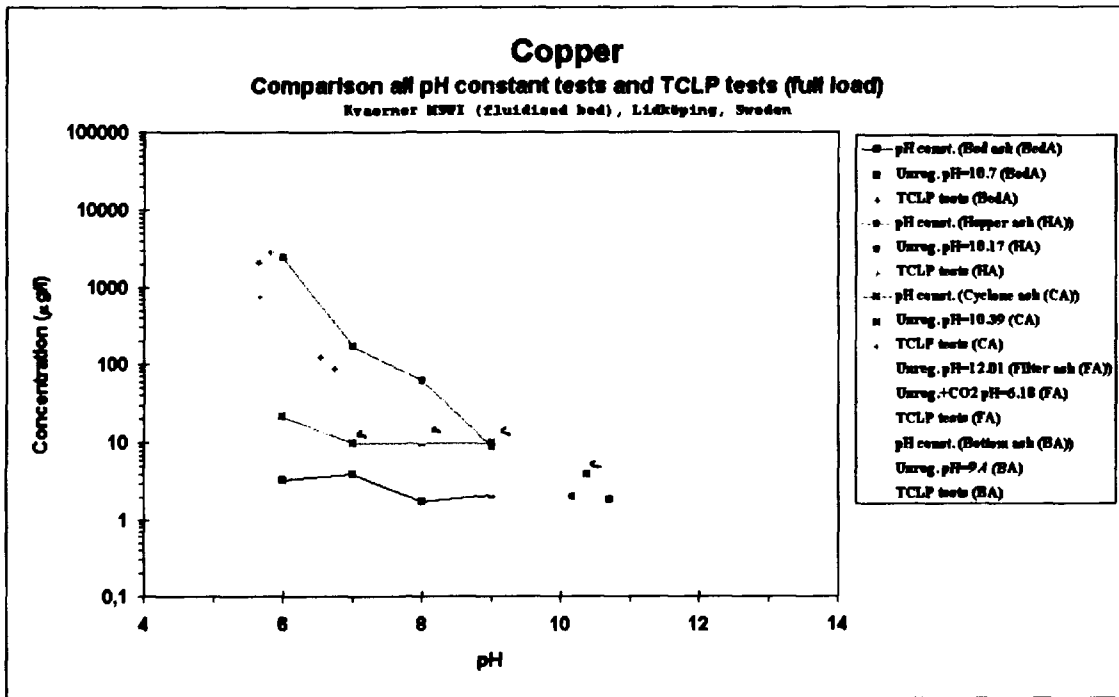
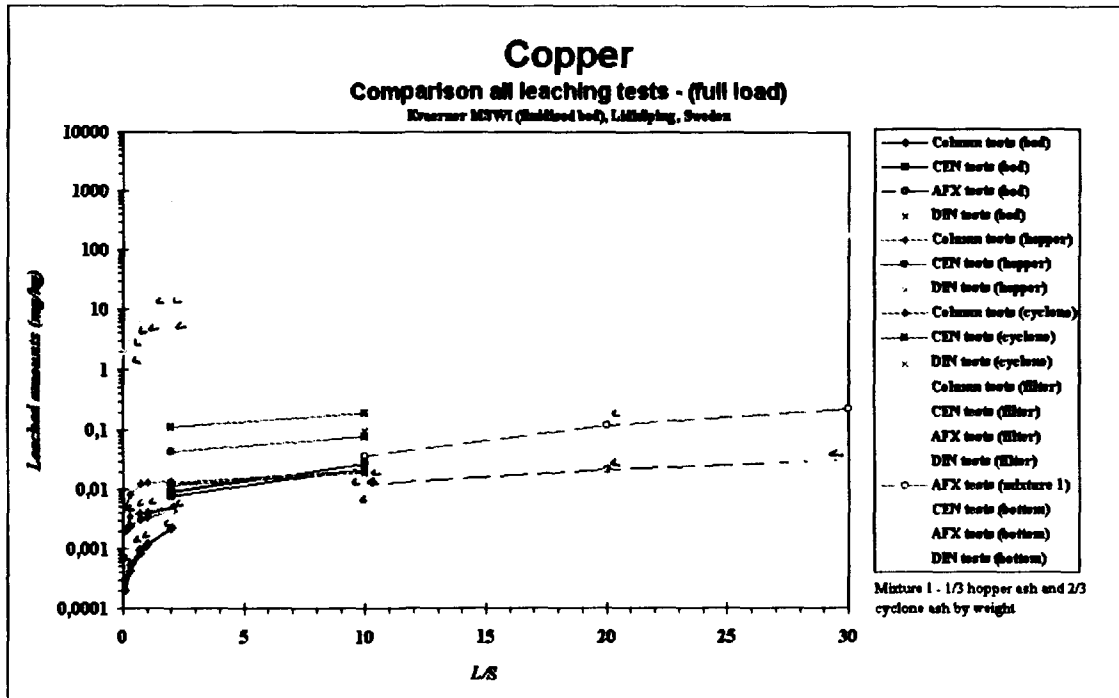
Mercury

Concentrations of Hg are in many cases below the detection limits (Figure 6.6) and no strong conclusions can be made from the results. The difference between AFX-tests and the available fraction is about two orders of magnitude. The pH-dependence is low, and probably it is the chloride concentration that determines the leaching rate of the (small) amounts Hg present.



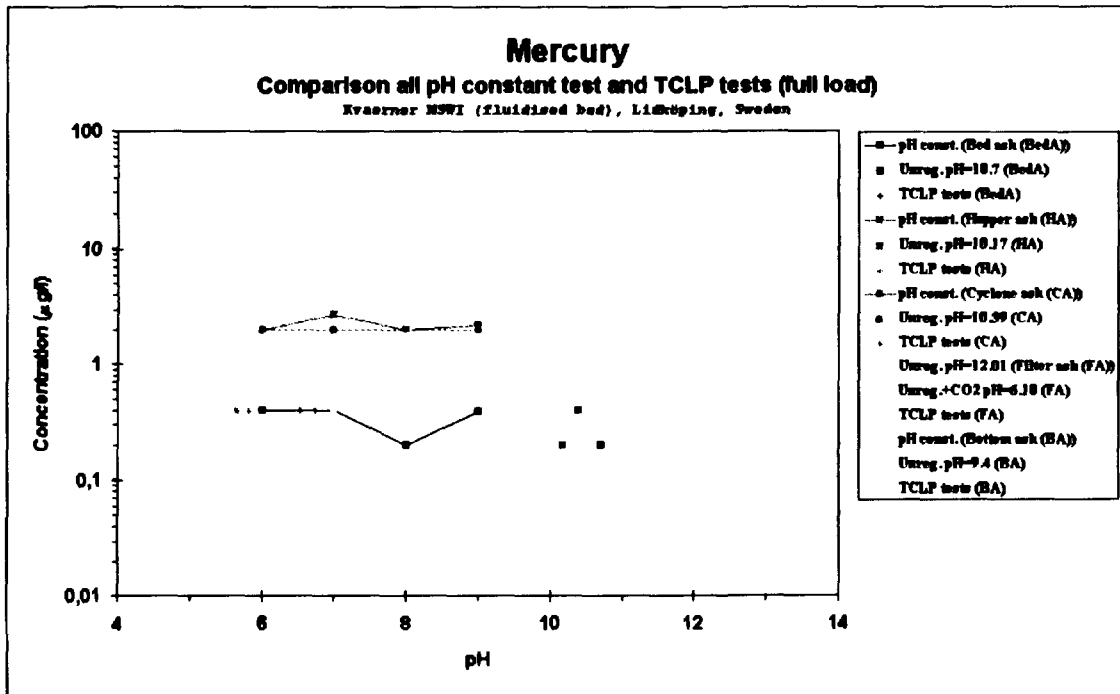
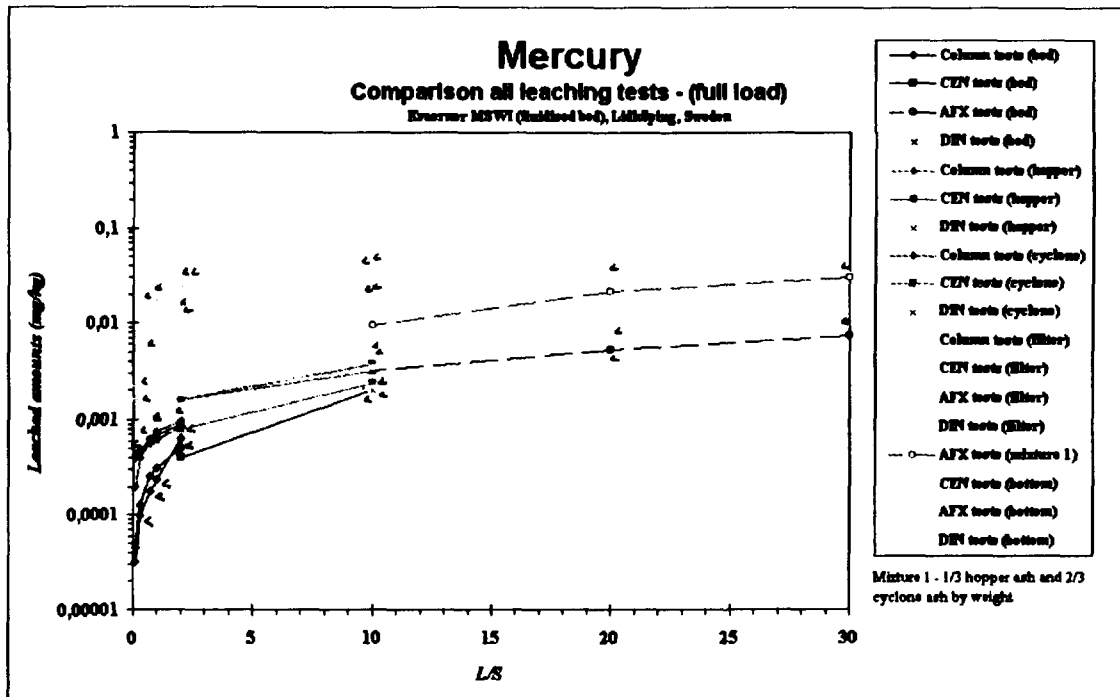
Note: Bed ash and hopper ash are no end products
 < denotes values below detection limits (shown)

Figure 6.4. Results from leaching tests for Chromium.



Note: Bed ash and hopper ash are no end products
 < denotes values below detection limits (shown)

Figure 6.5. Results from leaching tests for Copper.



Note: Bed ash and hopper ash are no end products
 < denotes values below detection limits (shown)

Figure 6.6. Results from leaching tests for Mercury.

Nickel

In many respects Ni is behaving similar to Fe. One important difference concerns the tendency of Fe(III) to form insoluble hydroxides. Fe is the one of the dominating element of the ashes and still there is lower concentrations of Fe than of Ni in the most of the leachates. Despite this, small amounts of Ni is leached, e.g. AFX is two orders of magnitude lower than the available fraction for bed and hopper ashes. TCLP and available Ni is of the same order (Figure 6.7) indicating that changes in pH can affect the leaching. There are a similar indication from the pH-static tests, however the leached amounts have been too small to be detected in most cases.

Lead

A somewhat increasing fraction of available lead have been noticed in the cyclone and filter ashes compared to bottom, bed and hopper ashes. It is not as pronounced as for Cu or Cd. About the same fractions of the total amount are available in the cyclone and filter ashes, instead of increasing amounts in the filter ashes. This could be explained by the high concentrations of sulphate found in the leachates causing supersaturation and precipitation of $\text{PbSO}_4(\text{s})$. Despite an L/S of 100 the concentrations of sulphate in the availability tests are 275 mg/l.

Concentrations in the pH-static tests are low, and somewhat surprisingly no pH-dependence is found in the pH-region (6 -9), except for cyclone ash.

Several species can affect the leaching of Pb. Both SO_4^{2-} and CO_3^{2-} can limit the amounts through precipitation of solid phases, but the high concentrations of Cl^- can instead increase the leachability of Pb through complexation. The leaching data give lower values than data from the availability tests (two orders of magnitude), except for the filter ash where the leached amount is similar to or even higher than the measured availability. It is possible that the available fraction in this ash is underestimated, because of SO_4^{2-} (see above). There is also a possibility that the very high pH (around 12) obtained in the CEN and AFX-tests may lead to an increase in the leachable Pb in the form of anions. Pb is also known to form soluble complexes with Cl^- in the same way as for Hg and to some extent Cd

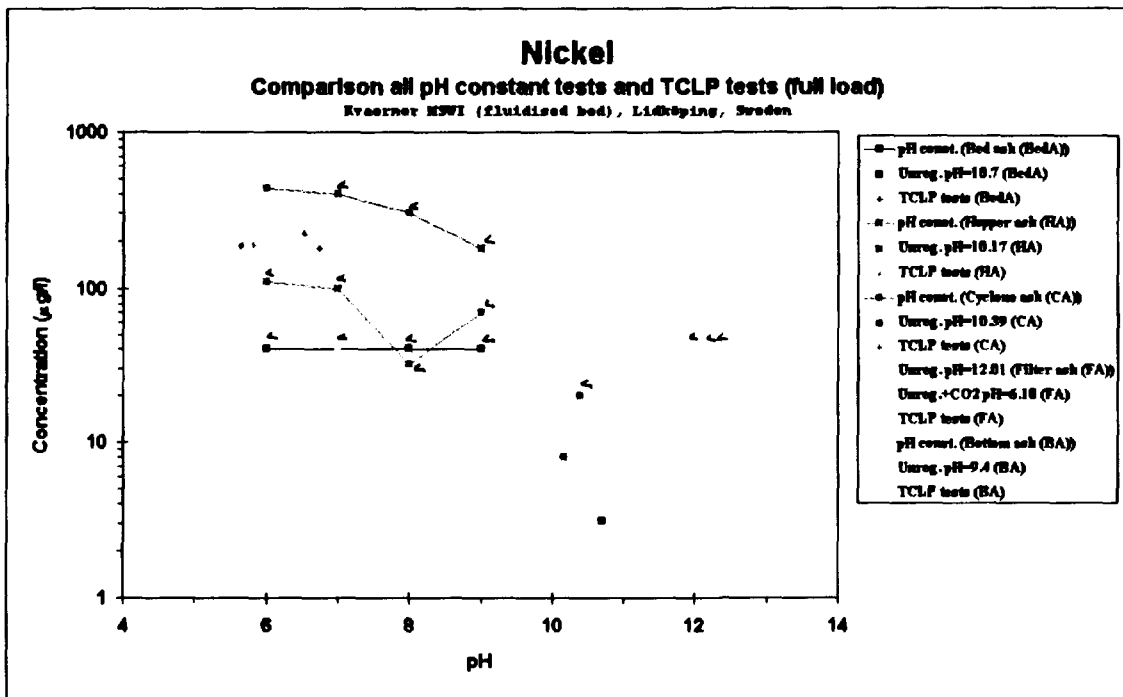
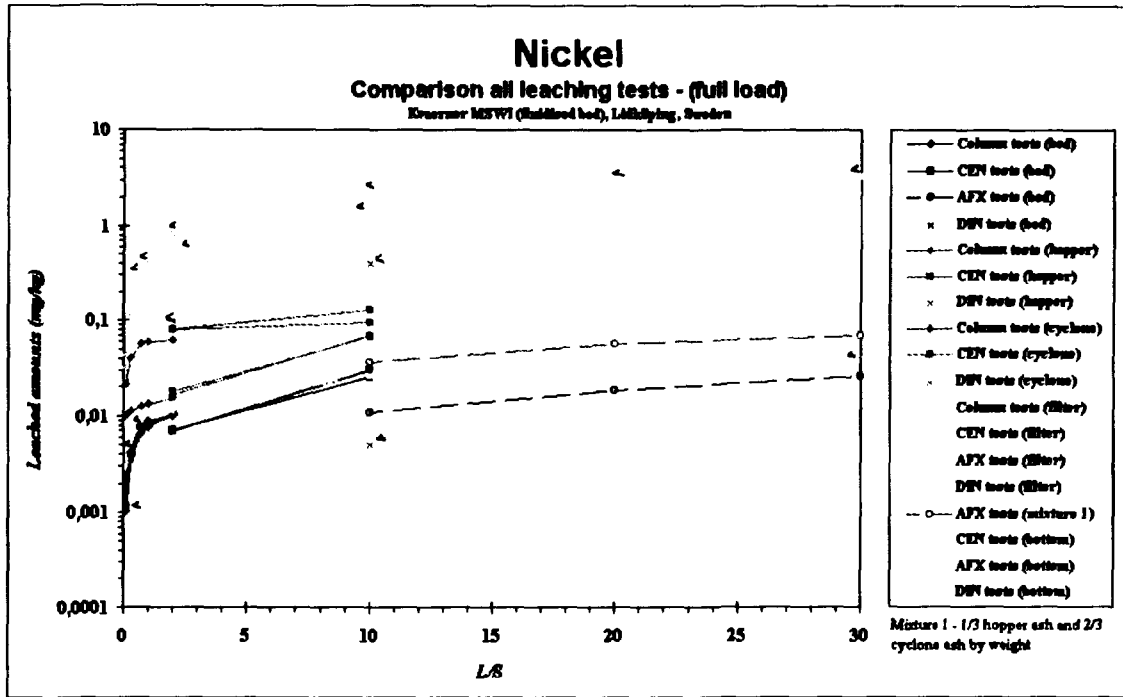
The column tests with the bed and filter ashes show higher leached amounts than the batch tests (Figure 6.8), but for hopper and cyclone ashes the leached amounts of Pb in the column tests are lower than what is found in the batch tests.

Zinc

A large portion of Zn is available in all ashes. Similar to Cd and Cu this portion increases from bed ash to filter ash and amounts to about 50 % in the filter ash.

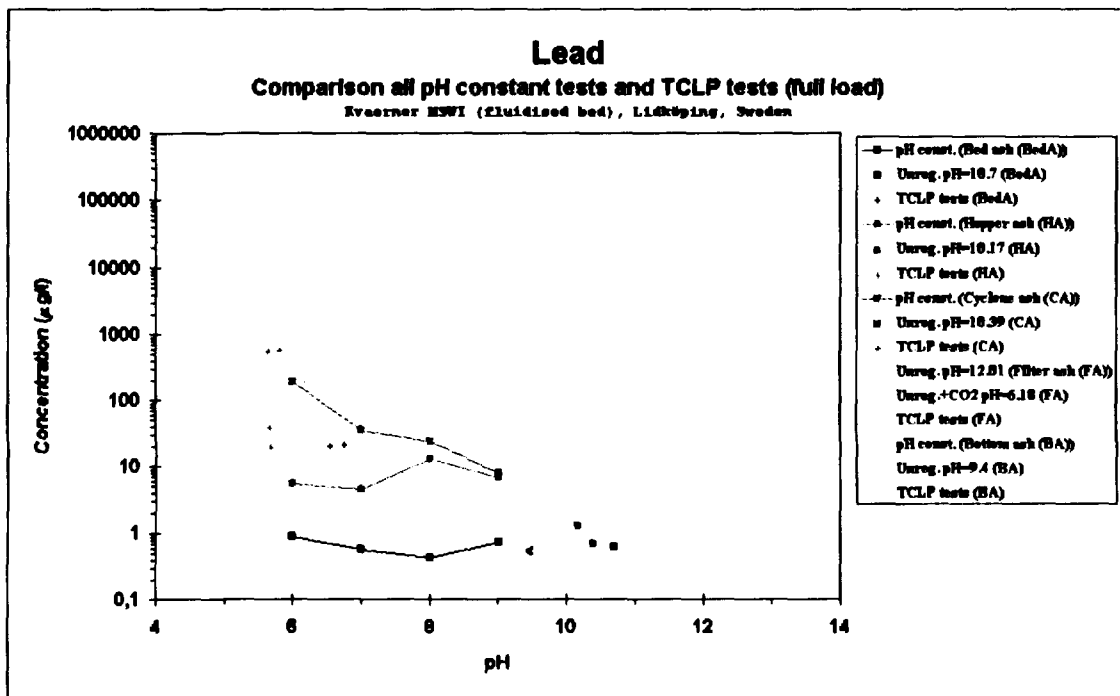
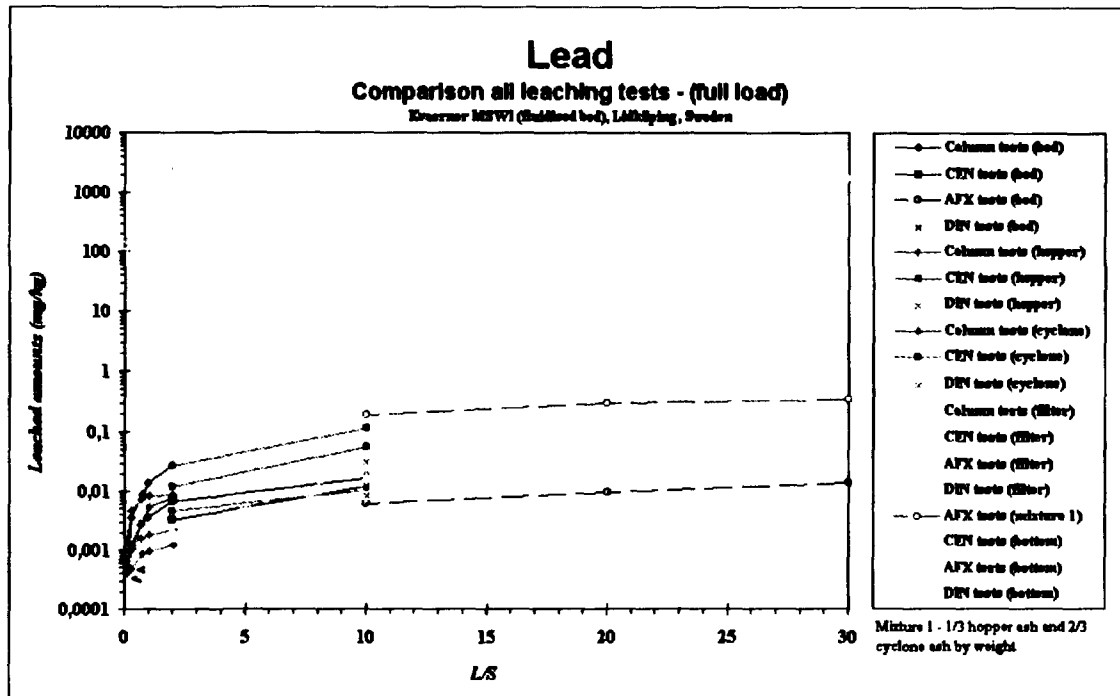
The leaching characteristics of Zn (Figure 6.9) is very similar to Cu. In the same way as for Cu the leaching seems to be very pH-dependent. The pH dependence in the pH-static tests possibly depends on adsorption or solid forms of ZnCO_3 .

As for Cd it is evident that leaching is more efficient in the filter ash than in the other ashes. Several orders (3 - 4) of magnitude lower leaching values than availability data was found for bottom, bed, hopper and cyclone ash. For filter ash, the difference was about two orders of magnitude. In the high pH-region (above pH 11) Zn can form anionic complexes such as Pb . This could explain the smaller difference between availability and other leaching data for the filter ash.



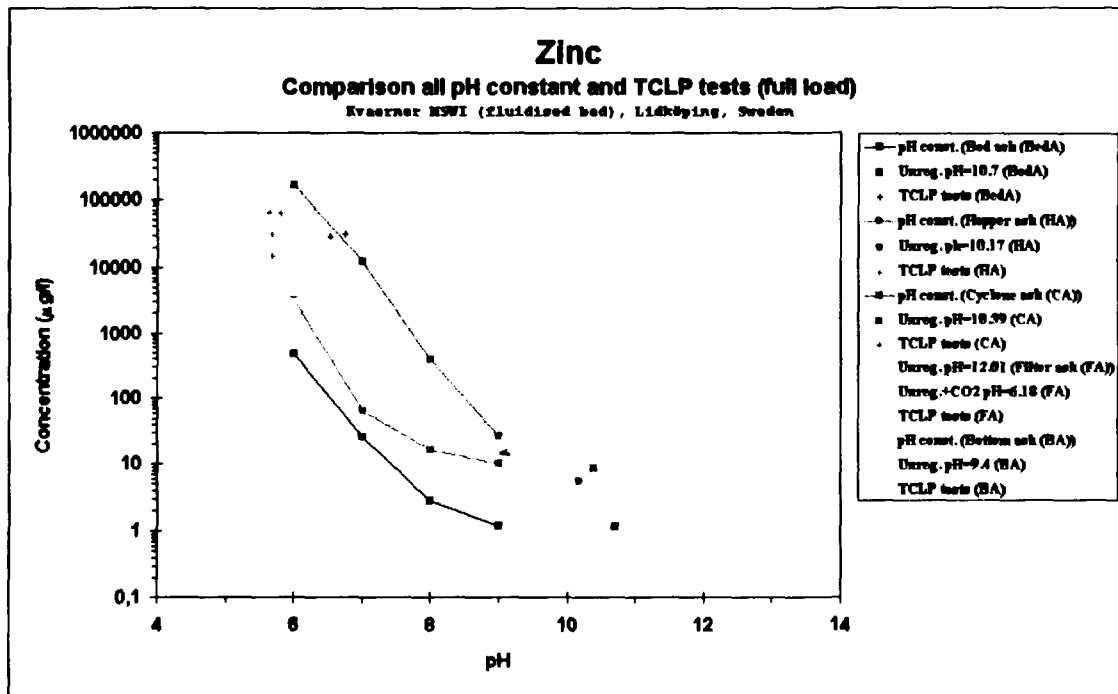
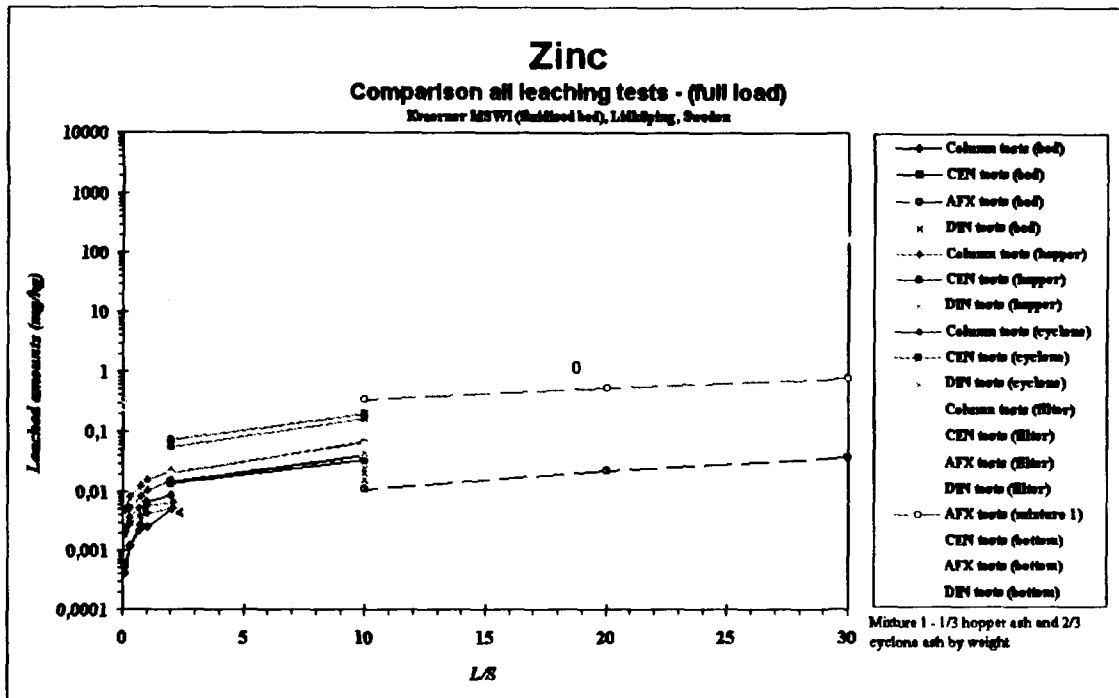
Note: Bed ash and hopper ash are no end products
 < denotes values below detection limits (shown)

Figure 6.7. Results from leaching tests for Nickel



Note: Bed ash and hopper ash are no end products
 < denotes values below detection limits (shown)

Figure 6.8. Results from leaching tests for Lead



Note: Bed ash and hopper ash are no end products
 < denotes values below detection limits (shown)

Figure 6.9. Results from leaching tests for Zinc.

6.2.2. Anlons

All tests show that chloride is easily leached. The L/S ratio determines the leachate amounts. For each ash, similar amounts are found in the CEN-tests, in the DIN-tests and from the columns.

For sulphate the differences are most pronounced between leached amounts in available and column tests with the cyclone and filter ashes. The content of SO_4^{2-} in the leaching tests and columns could be limited by the formation of $\text{CaSO}_{4(s)}$.

Fluoride is found in moderate concentrations in the DIN-tests. An increase in the leaching could be expected due to complexation with Al, while a decrease in leaching is expected from the formation of CaF_2 .

6.2.3. Comparisons between full load and low load

Leachable amounts from ashes produced under low load conditions, measured by CEN-tests, are similar to what is leached from ashes produced under full load conditions. Differences are mainly found in the hopper ash fraction where leached amounts are somewhat higher in the low load case for Pb, Zn and Cr. On the other hand, leached amounts are lower for As, Ni and Cd. Decreasing or similar amounts is found for the other elements in the other ashes.

In the full load case, Cr(VI) is found only in leachates from the bed ash, while in the low load case it is also found in the hopper and to some extent in the cyclone ash. Since the availability tests indicate similar amounts between the loadings, this effect could be due to a higher surplus of air during combustion thereby creating more favourable oxidizing conditions. A change in size distribution is also noticed. Smaller grain size is found for the low load case, most evident for bed and hopper ashes.

6.3. Physical characterization

6.3.1. Grain density

The grain density was highest for the filter ash and lowest for the hopper ash (Table 6.5). In the bed ash the grain density is similar to what is expected for the bed material, (for quartz $\rho_s = 2,65 \text{ t/m}^3$). The results does not indicate any major differences in grain density between high load and low load.

Table 6.5 Measured grain densities

	Bed ash ¹⁾	Hopper ash ¹⁾	Cyclone ash	Filter ash
Full load	2,61	1,87	2,40	2,80
Low load	2,64	1,81	2,38	2,83

¹⁾ No end products

6.3.2. Grain size distribution

With respect to the grain size distribution bottom ash can be characterized as a medium graded gravelly sand while bed ash can be described as a gravelly sand, hopper ash as a sand, cyclone ash as a sandy loam, and filter ash is a silt. The grain size distribution is shifted towards smaller sizes in the low load case, but without changes in the classification. All primary ashes (bed, hopper, cyclone and filter ashes) can be characterized as uniformly graded.

The distribution for bottom ash represent the material that was artificially produced in laboratory by sieving bed ash and mixing with hopper ash. Laboratory testing, e.g. leaching tests, generally were performed on this material. However, depending on small amounts available, compaction tests were performed on a sample taken directly from the plant about one year later. This sample showed a somewhat different grain size distribution, see Chapter 6.3.3.

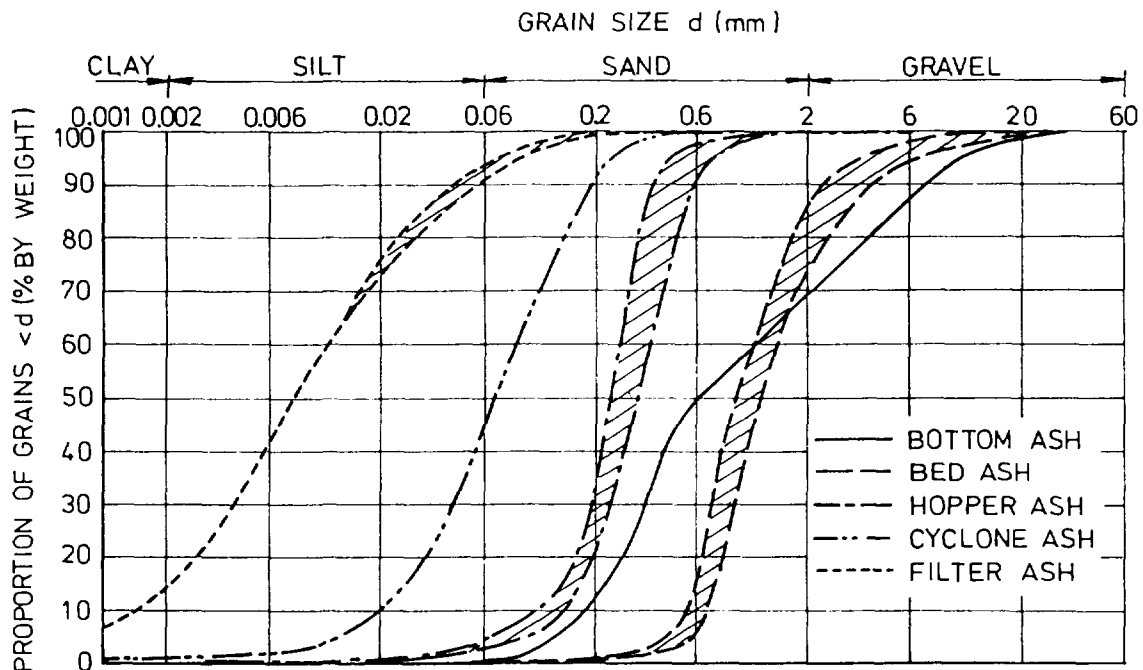


Figure 6.10. Grain size distributions for the different ashes.

6.3.3. Compaction tests

Modified Proctor compaction tests have been determined for the bottom and cyclone ashes. The results are shown in Figure 6.11.

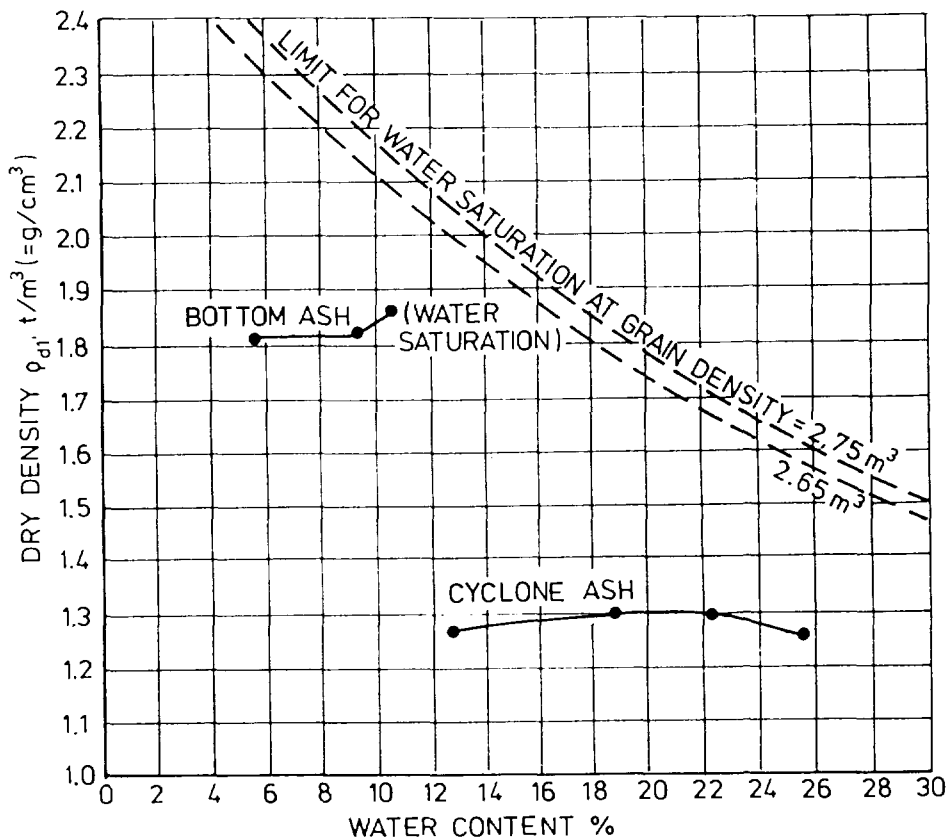


Figure 6.11. Results from compaction tests

The optimum water content for compaction of cyclone ash is about 20 % and the obtained maximum dry density is about 1.3 t/m³. According to the test, the compaction result (measured as dry density) is not very sensitive to the water content as the curve is rather flat. In practice though, problems may arise with compaction due to the uniformly graded character of the ash ($C_U=4$). The low density that was reached in the compaction test might have been an effect of this, i.e. no compaction effect was gained in the test.

The bottom ash showed the highest degree of compaction at a water content between 10 and 11 %. At this water content the sample was saturated with water. The maximum dry density reached was about 1.85 t/m³. This is about the same as the grain density of the hopper ash that constitute a large fraction of the bottom ash and indicate that a good compaction effect was gained. A certain crushing of particles was noticed in Proctor compaction tests as shown in Figure 6.12. The material showed very little sensitivity to the water content, the compaction result was at the least 97 % of the maximum dry density in all compactions. It should also be observed that, depending on small amounts available, compaction tests with bottom ash was performed on a sample taken about one year later than other samples. This sample showed a somewhat more coarse-grained grain size distribution as can be seen by a comparison between the bottom ash grain size distributions showed in Figure 6.11 and Figure 6.12.

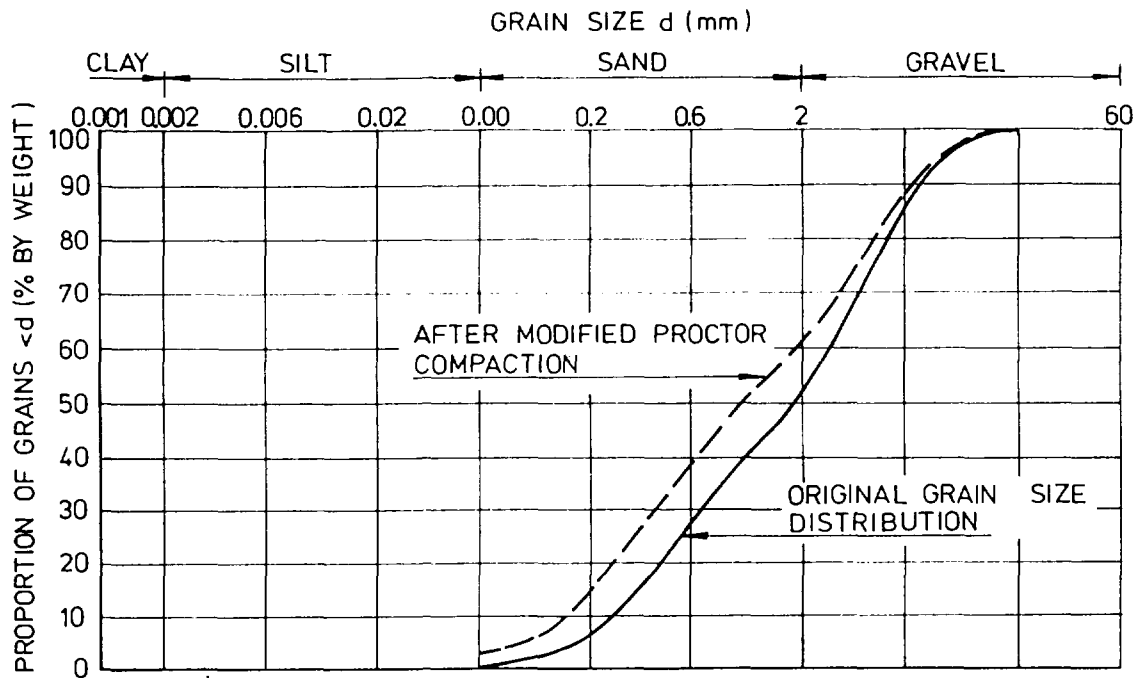


Figure 6.12. Grain size distributions for bottom ash before and after Proctor compaction tests.

6.3.4. Stabilization of cyclone ash

Investigations of cyclone ash stabilized with cement were performed on four different mixes and one reference without cement according to Table 6.6.

Table 6.6 Mixtures investigated for cement stabilization of cyclone ash

Mixture No	Cement content (% of dry matter)	Water content (% of dry matter)	Comments
1	5	22	compacted at opt. water content
2	10	22	compacted at opt. water content
3	5	adjusted for casting	cast
4	10	adjusted for casting	cast
5	-	22	compacted at opt. water content

The uniaxial compressive strength was measured on all samples after curing in 7, 14 and 28 days. After 28 days of curing also the permeability (saturated hydraulic conductivity) was measured.

Results from the uniaxial compression tests are shown in Figure 6.13. For the cast samples low strength were measured at all times (No 3 and 4). For the compacted samples relatively high strength were measured after 7 days of curing. The mixture with 10 % cement (No 2) showed the highest strength at this time while the mixture with 5 % cement (No 1) and the reference sample (No 5) showed about the same result. However, for the mixture with 10 % cement the strength decreased with time. For the mixture with 5 % cement the strength had

decreased in the samples tested at 14 days but increased in the samples tested at 28 days. The strength for the reference sample showed some decrease with time. The results indicate that the chemistry of the hardening reactions have to be studied before any conclusions can be drawn. Probably there are slow reactions which is negative for the hardening in a longer term perspective. One obstacle can be formation of hydrogen gas which can take place when water is added to the cyclone ash and causes swelling.

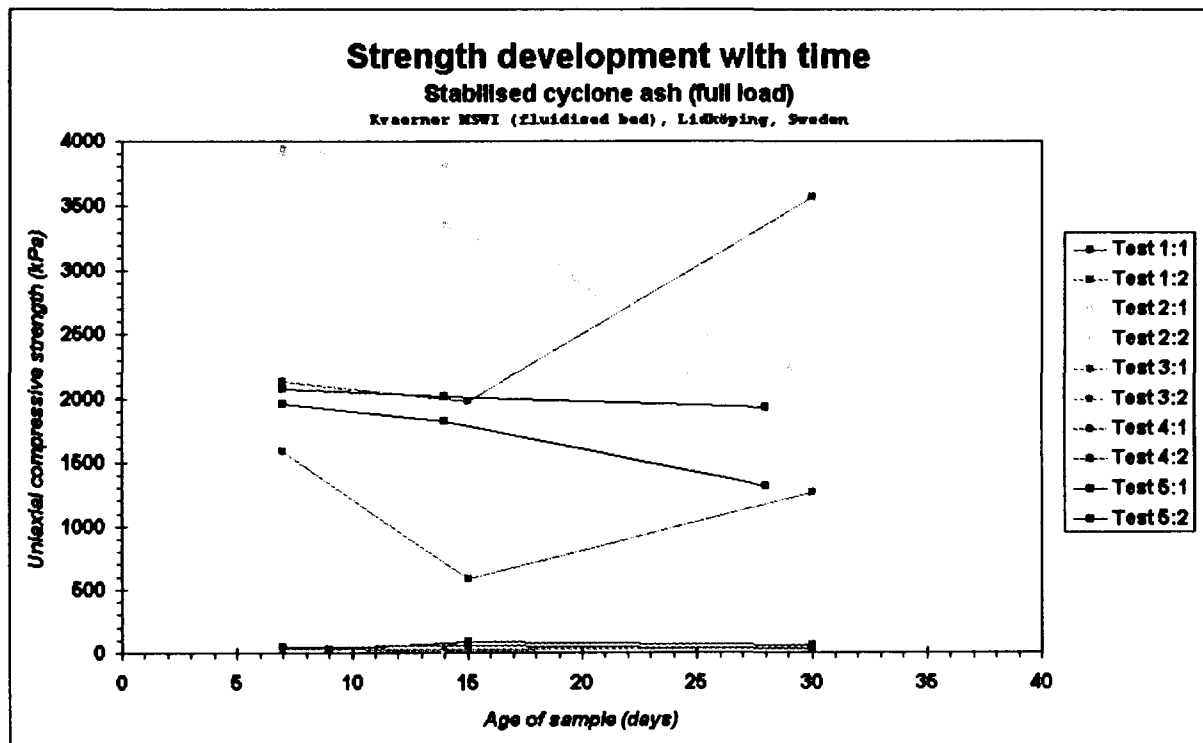


Figure 6.13. Unconfined compressive strength of stabilized cyclone ash as a function of time.

The permeability tests show for most of the samples varying results with time (Figure 6.14). This was most probably an effect of hydrogen gas formation which involved varying water saturation with time. However, it can be concluded from the results that the stabilized products that were investigated showed to high permeabilities to be considered as low permeable products. They do not fulfil e. g. normal demands on sealing layers.

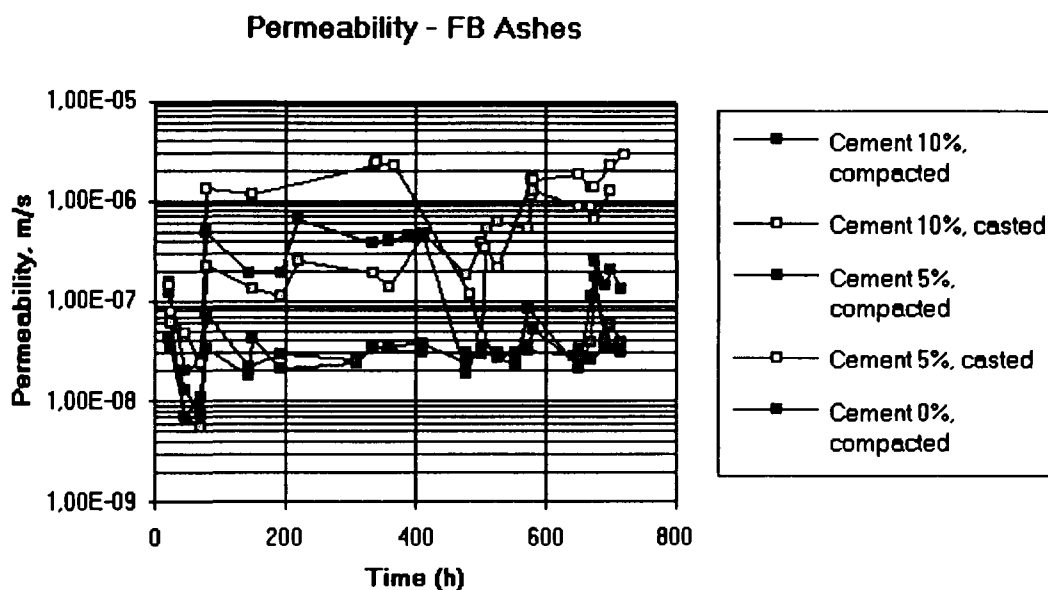


Figure 6.14. Measured permeabilities of stabilized cyclone ash.

7. COMPARISON WITH ASHES FROM MASS BURN WASTE INCINERATION

7.1. Total contents

The total content of main components and trace elements in the ashes from the fluidized bed (FB) incinerator in Lidköping compared to ashes from mass (MB) burn incinerators in Sweden are shown in Table 7.1.

No data have been found on the chemical composition of hopper ash from other MSWI incinerators in Sweden. For the mass burn incinerators referred to in Table 7.1, hopper ash usually constitute a fraction of the bottom ash.

From Table 7.1 it appears that the concentration of silicon was higher in the bottom ash from the FB incinerator than in bottom ashes from MB incinerators. This is probably an effect of the sand content in the fluidized bed. It can also be concluded that the calcium content was lower in the bottom ash from FB than in bottom ashes from MB. Instead, the calcium content in the cyclone ash and the filter ash was higher than in fly ash and APC residues from MB.

The content of unburnt matter was considerably lower in the FB ashes than in corresponding MB ashes.

The trace element contents in the FB ashes were mostly within the range measured for corresponding ashes from MB incineration technique. However, some differences can be noticed. The distribution of lead in the FB ashes was different compared to MB ashes, with a somewhat lower concentration in the bottom ash (and hopper ash) and a higher concentration in the filter ash. A similar effect can be noticed for copper showing a higher concentration in

the FB filter ash than in APC dry and wet process residues from MB incinerators. The copper concentrations in the other FB ashes, though, were within the range for MB bottom ashes.

Table 7.1 Total content in the ashes in comparison with ashes from massburn incinerators in Sweden.

	Fluidized bed, Lidköping Gross sample (mean)				Mass Burn ²			
	Bottom ash	Hopper ash ¹⁾	Cyclone ash	Filter ash	Bottom ash	Fly ash	APC ³ Dry Residues ⁴	APC ³ Wet Residues
	%				%			
SiO ₂	64.9	64.4	42.8	7.0	49.8-60.0	31.6-63.6	4.4-14.0	14.9-17.1
Al ₂ O ₃	12.0	13.2	22.4	4.2	11.2-13.6	11.5-20.6	2.5-8.1	6.9-7.6
CaO	7.7	7.7	16.8	50.8	11.0-13.6	9.4-15.5	26.4-34.9	36.9-38.6
Fe ₂ O ₃	4.4	4.9	4.9	0.8	5.3-7.0	2.0-5.7	0.2-1.1	3.1-3.6
K ₂ O	2.6	2.4	2.1	1.0	1.6-2.7	2.6-7.2	1.9-3.1	≤0.1
MgO	1.5	1.3	2.7	1.7	2.1-3.2	2.0-4.6	1.3-2.5	4.2-5.9
MnO	0.1	0.1	0.3	0.1	<0.1-0.2	0.1-0.6	<0.1-0.8	0.2
Na ₂ O	4.7	3.4	3.4	1.8	4.8-6.9	2.9-5.7	2.1-3.3	0.1-0.2
P ₂ O ₅	0.9	1.1	1.6	0.9	1.4-2.9	1.2-2.5	0.3-0.8	0.4
TiO ₂	0.8	0.9	1.2	0.3	0.7-1.0	0.5-2.1	<0.1-0.4	0.1-0.2
Unburnt	<0.1	0.08	0.3	0.02	3.0-4.9	4.9-9.8	0-6.4	2.4-4.5
	mg/kg				mg/kg			
As	49	5	46	80	20-80	40-140	<10-80	30-40
Ba	1190	1300	2200	800	90-1600	870-2300	190-660	150-180
Cd	7.1	6.4	9.5	89	4-40	0.3-110	130-180	70-100
Co	26	19	34	20	<10-40	<10-15	<10	<10
Cr	350	280	407	200	300-600	260-2400	140-450	300-650
Cu	3000	3200	3100	5400	900-3200	700-5000	300-630	400-550
Hg	1.4	<0.3	<0.3	2.8	<0.01-3	2-40	8.8-100	1200
Mo	70	28	23	13	20-40	15-50	60-80	30-50
Ni	160	88	120	30	60-160	80-200	20-50	350-750
Pb	840	680	1100	6000	1300-5400	1200-3600	2200-3300	2300-2900
Sn	140	120	29	20	<100-1300	<100-810	500-600	300-450
Sr	280	230	350	500	190-350	270-550	100-400	160-170
V	36	44	54	14	50-90	60-110	<20-30	70-90
W	100	<40	<20	<10	<20-50	<20-90	<20	<20
Zn	3200	2800	6000	6000	1800-5900	2500-14000	7800-11400	5700-6400

1) No end product

2) Hartlén & Elander, 1986

3) APC - Residues from Air Pollution Control

4) Including Semi-Dry Process Residues

The concentrations of mercury were generally lower in the FB ashes than in corresponding MB ashes. Partly this might be valid also for cadmium. This is certainly an effect of an increased source separation of batteries which have taken place since the MB ashes were analysed.

7.2. Leaching characteristics

Several leaching tests on MSWI ashes have been carried out during the past ten years. Unfortunately, testing is performed according to different procedures in different countries. Procedures for leaching also differs within a single country. For instance, Swedish ashes from MB incinerators have only been investigated according to an old procedure, the so called ENA-test, which is no longer in use. Different procedures involve leaching at different governing conditions such as pH, proportions between liquid and solid phase, agitation etc. This implies certain difficulties when it comes to comparison of leaching characteristics between the investigated FB ashes and MB ashes.

However, leaching data from tests carried out in the US, Canada, Sweden, Germany, Denmark and the Netherlands have recently been put together within the limits of an ongoing work covering the whole area of characterization and management of MSWI residues conducted by IAWG (International Ash Working Group). From this work it is concluded that column tests usually are performed in a similar manner and are useful for comparisons of the leaching from different ashes as a function of time (i e L/S-ratio).

In the comparisons with other plants, data from the full load case are used.

7.2.1. Bottom, bed, hopper and cyclone ash

In Figure 7.1 results from column tests on bottom ashes from MB (International Ash Working Group) are put together with the results from the corresponding tests with bed, hopper and cyclone ashes from FB (for the bottom ash no column tests have been performed).

Arsenic

The total contents of As in the investigated FB ashes (bottom, bed, hopper and cyclone ash) were within the range for bottom ashes from MB according to Figure 7.1. The availability of As in the FB bed ash was high compared to MB bottom ashes while the release in the column tests was similar. For bottom ash, hopper ash, and cyclone ash the availability was in the range for MB bottom ashes. On the other hand, the release in the column test was about one order of magnitude higher than from MB bottom ashes at L/S 2. It should be noticed that just a few measurements of the release of As from MB ashes are found.

Cadmium

The total content of Cd in the FB bed ash was relatively low compared to MB bottom ashes while the total content in hopper and cyclone ash were in the middle of the range shown in Figure 7.1. For the bed ash the availability was lower than the availability for investigated MB ashes, while the availability for the bottom, hopper and cyclone ashes lie within the interval for MB bottom ashes. The release of Cd from the FB ashes in the column test are comparable to the lowest measured release for MB ashes.

Chromium

The total content of Cr in the FB ashes were in the range for investigated MB bottom ashes. The availability for Cr in bottom and hopper ash were similar to MB ashes while the measured availability in bed and cyclone ash from FB were higher than the availability in MB bottom ashes. Most significant is the release from the FB primary bed ash in column test which was higher than the reported release of Cr from any of the MB bottom ashes. This might be an effect of the efficient combustion in FB, which may have transferred Cr(III) to the more

mobile form Cr(VI). In contrary, the release of Cr in column tests from the hopper and cyclone ash in the full load case was within the interval for MB ashes. From the batch tests it can be concluded that the release of chromium from the bottom ash was comparable to or even lower than the release from the primary hopper ash.

Copper

Total concentrations of Cu in the FB bottom, bed, hopper and cyclone ashes, as well as the availability, were higher than for the investigated MB bottom ashes. Despite this, the release of Cu in column tests was considerably lower for the FB ashes. This might be a function of the low organic content in the FB ash, as Cu is known to form strong complexes with dissolved organic matter.

Nickel

The availability and release of Ni shows strong similarities with the leaching behaviour of Cu, with the exception that the release from cyclone ash was within the range for MB ashes. Ni as well as Cu is known to form complexes with dissolved organic matter.

Lead

The total content of Pb in bottom, bed and hopper ashes were somewhat lower than in MB bottom ashes while the content in cyclone ash was within the range. For bed ash and bottom ash but not for hopper ash also the availability was lower. The release in column tests in general were low compared to MB bottom ashes.

Zinc

The total content of Zn in bottom, bed and hopper ashes were similar to MB bottom ash while the availability were somewhat higher. The release in column tests were comparable to the lowest measured release for MB ashes. For cyclone ash the total content as well as the availability were higher than for MB bottom ash. Despite this, the release in column tests were in the lower part of the range for MB ashes.

Chloride

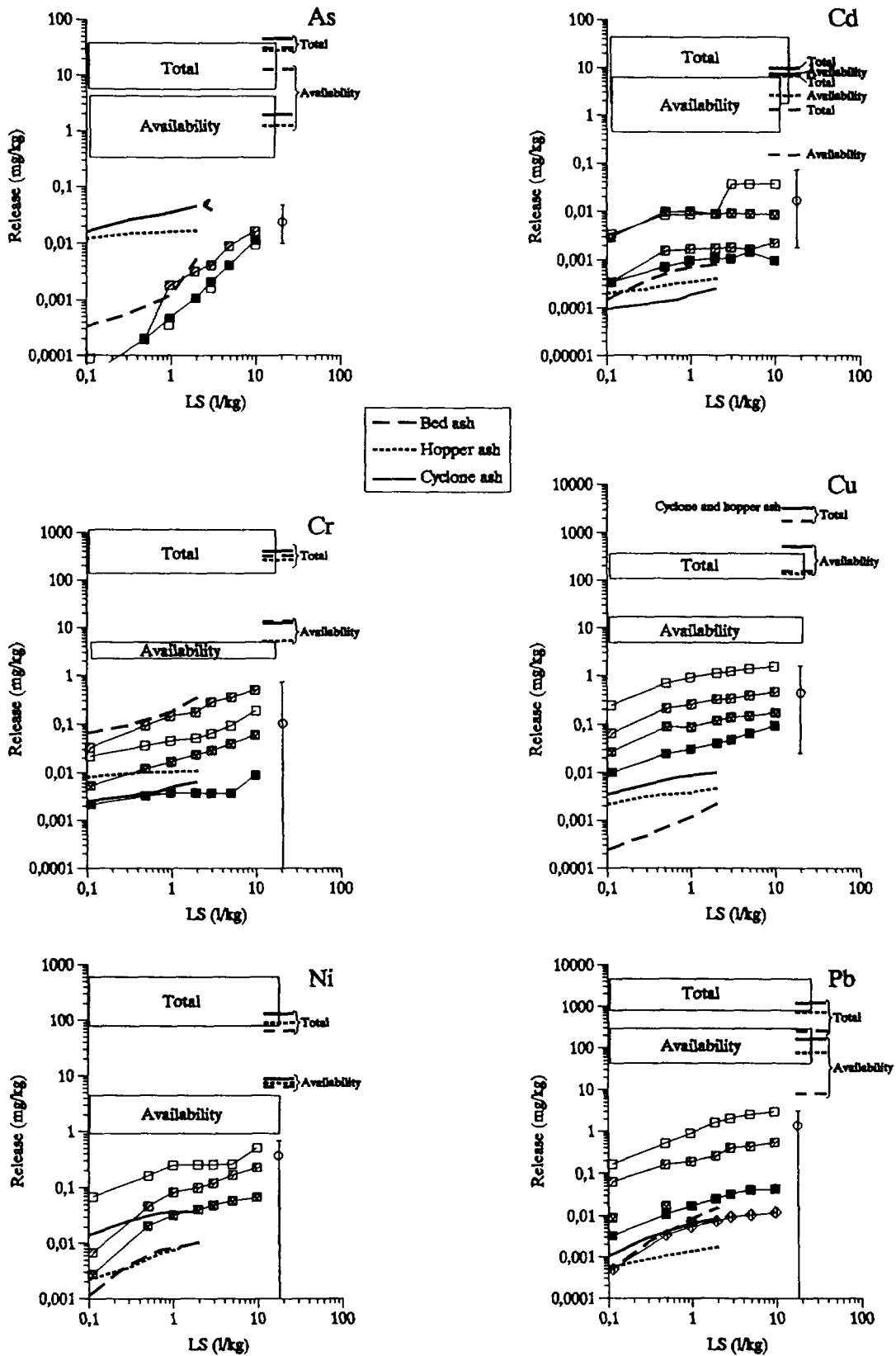
The measured release of Cl⁻ from cyclone ash and hopper ash including the mixture with the coarse fraction of bed ash in column tests are comparable to the results from MB bottom ash, while the release of Cl⁻ from FB bed ash was remarkably lower. For bed and hopper ash the availability was comparable to MB bottom ash. For cyclone ash the availability was considerably higher.

Conclusions

The investigated bottom, bed, hopper and cyclone ashes are principally comparable to bottom ashes from mass burn with respect to the content, availability and release of trace elements. For most of the elements, the release from FB ashes is low compared to the reported release from MB bottom ashes. This is valid for Cd, Cu, Ni, Pb and Zn.

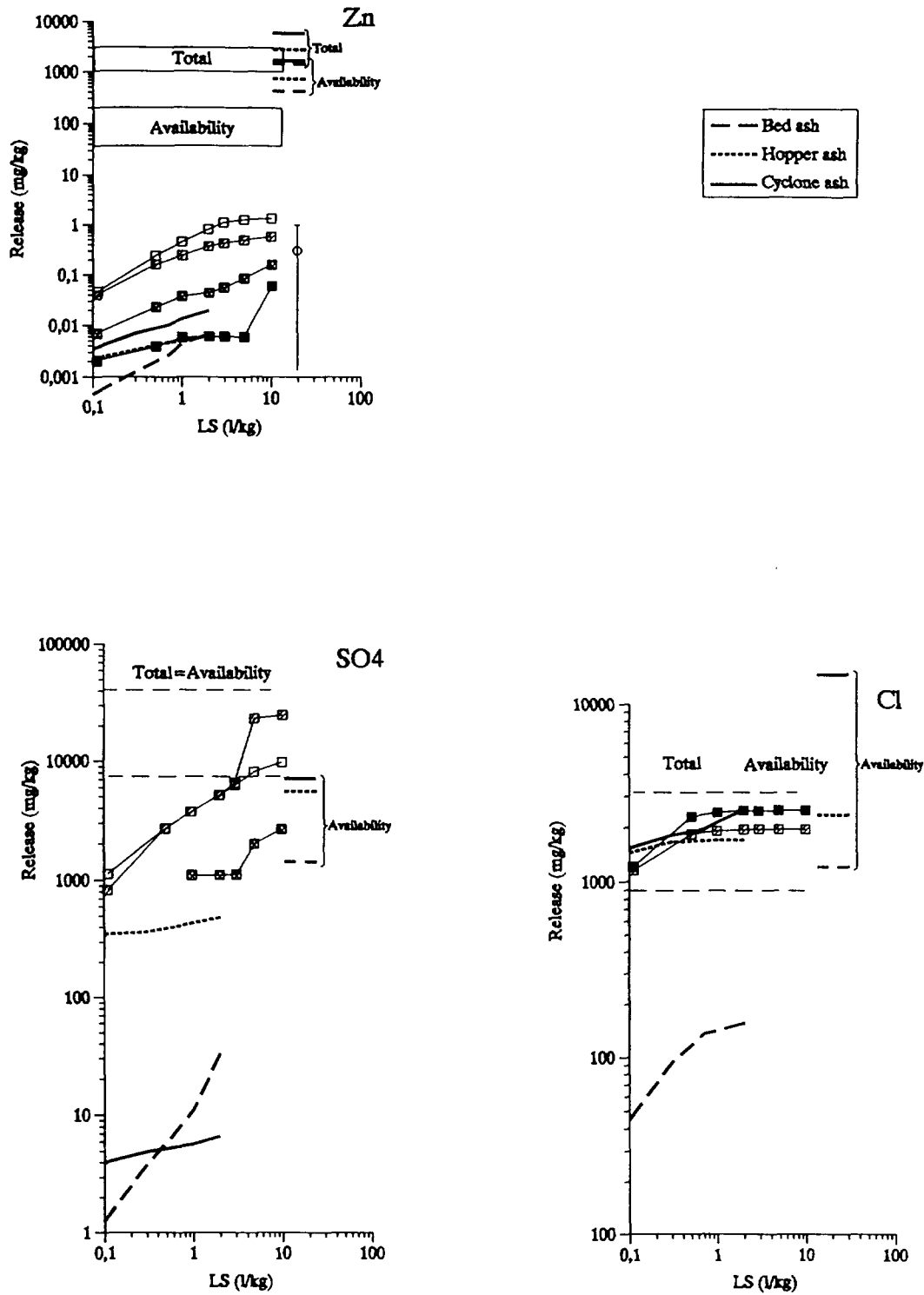
The most significant difference is the relatively high release of Cr(VI) from the primary bed ash from FB. This however, should not constitute a problem since the bed ash to a considerable extent is recycled and no release of Cr(VI) from the bottom ash that leaves the plant could be found.

It should also be noticed that the measured release of As from cyclone and hopper ash were higher than what is reported for MB bottom ash. However, the release still is rather limited.



Note: Bed ash and hopper ash are no end products
 < denotes values below detection limits (shown)

Figure 7.1 (a) Results from column tests on bottom ashes from mass burn incinerators (data from IAWG) in comparison with the results from column tests on bed ash, hopper ash and cyclone ash from the Lidköping BFB plant.



Note: Bed ash and hopper ash are no end products
 < denotes values below detection limits (shown)

Figure 7.1 (b) Results from column tests on bottom ashes from mass burn incinerators (data from IAWG) in comparison with the results from column tests on bed ash, hopper ash and cyclone ash from the Lidköping BFB plant.

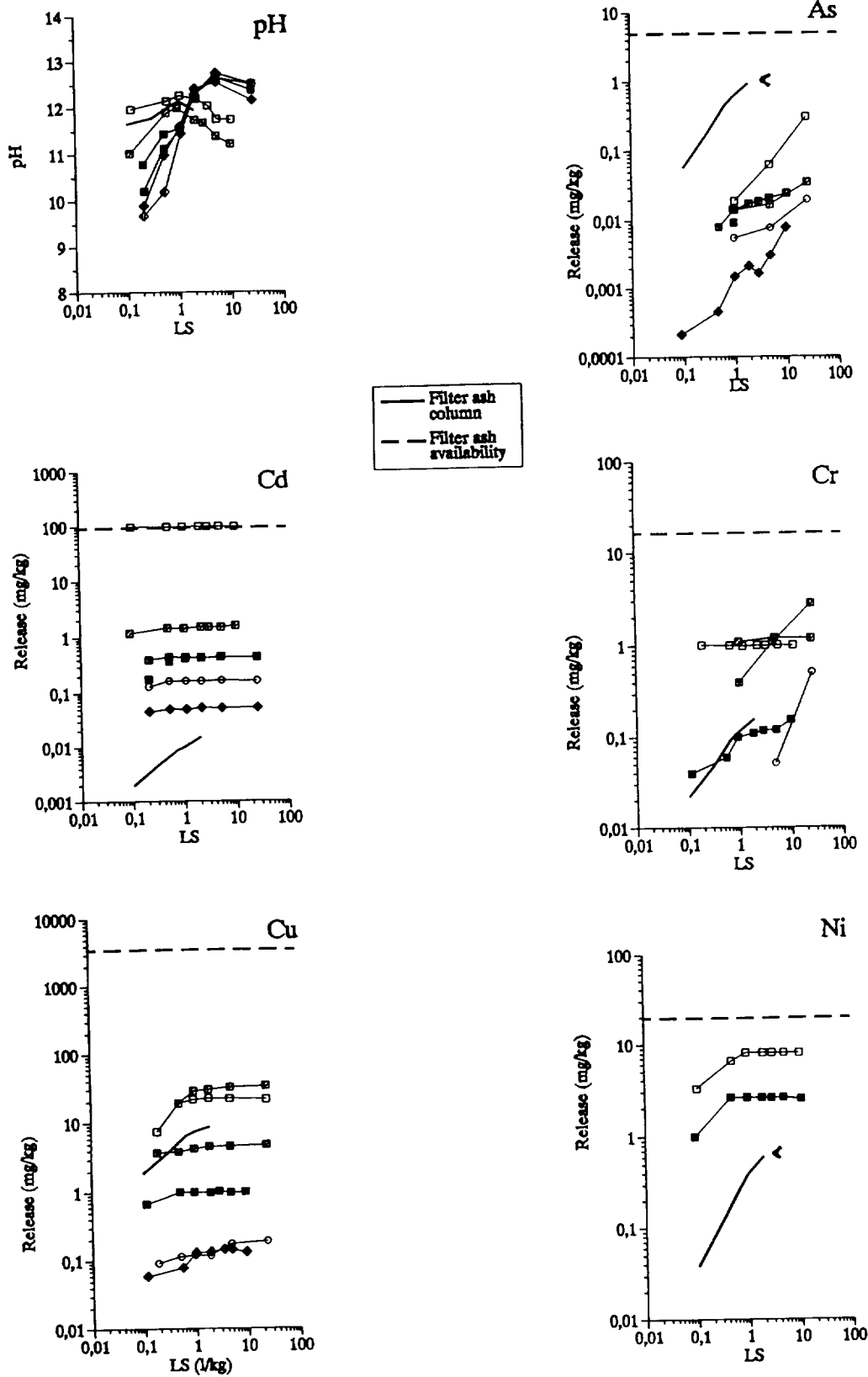


Figure 7.2 (a) Results from column tests on filter ash from the Lidköping plant compared to APC residues from mass burn incinerators (data from IAWG

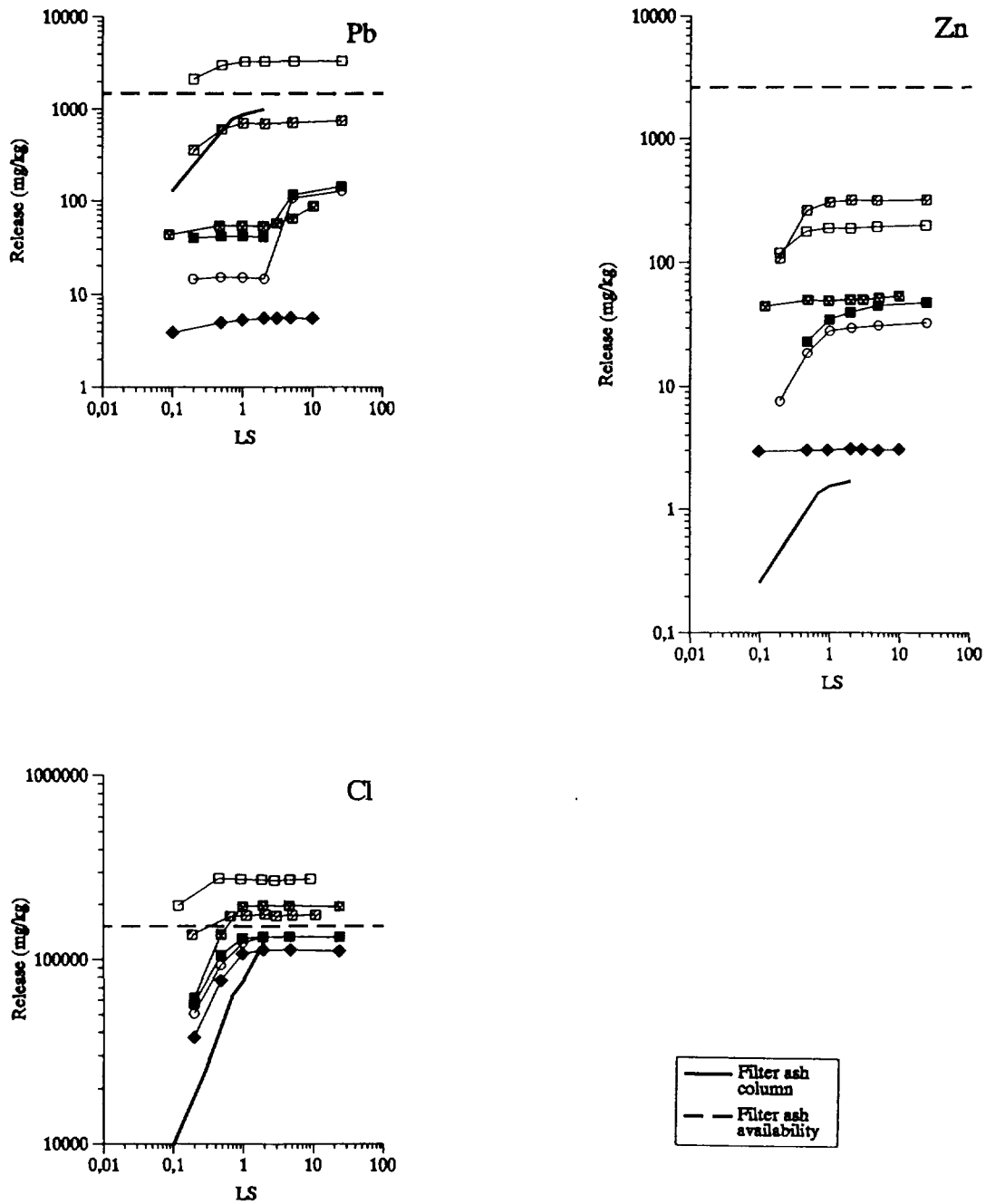


Figure 7.2 (b) Results from column tests on filter ash from the Lidköping plant compared to APC residues from mass burn incinerators (data from IAWG).

7.2.2. Filter ash

In Figure 7.2, the release of trace elements from the filter ash in column tests are compared to the release from different types of APC (Air Pollution Control) residues from other MSWI plants.

From the leaching curves for APC residues in Figure 7.2 it can be concluded that the cumulative release increases only slightly after an L/S=1. This implies that the amount washed out represents soluble chemical species washed out at the actual pH controlled by the residue. The primary exceptions are the release of As and for some installations Cr.

The measured release from FB filter ash were somewhat different for Cd and Ni, with an increasing cumulative release with time up to L/S 2 (end of the test). The cumulative release of these elements at this point was lower than reported for APC residues. For Cr, Cu, Pb and Zn the leaching curves for FB filter ash were similar to the release reported for other APC residues. For Cr, Cu and Pb the cumulative release were within the range for APC residues while the cumulative release of Zn was lower.

For As the release from the filter ash during the test was higher than the release from other APC residues indicating a faster leaching of As from the filter ash.

The cumulative release of Cl⁻ from FB filter ash was lower at low L/S-ratios, but in the range for APC residues at L/S 2.

8. CONSIDERATIONS FOR HANDLING AND DISPOSAL

8.1. General

Legislation regarding handling and disposal of residues is based on different principles in different countries. In some countries handling and disposal practice for a residue is governed by results from analyses of the residue compared to different sets of limit values. Classification is based primarily on analyses of total contents and/or leaching in specified standard tests. One set of limit values can be prescribed for a product to be accepted for utilization and other sets of limit values are used to classify the product in different classes according to landfill disposal procedures. In other countries, e.g. Sweden, disposal procedures have to be decided upon in each individual case according to the characteristics of the residue in combination with the specific environmental conditions for the site in question. Such a procedure involve the evaluation of an environmental impact assessment for each case.

The differences in environmental legislation involves different handling and disposal procedures for the same residue in different countries.

8.2. Swedish disposal practice

According to the Swedish legislation, procedures for handling and disposal shall be based on an environmental impact assessment for each landfill or utilization object. Such an environmental impact assessment involve calculations of release of contaminants from an utilization object or landfill in comparison to background levels. The release of contaminants

is governed not only by the leaching characteristics of the residue, but also by factors such as the water balance for the object.

For general estimates of necessary precautions in disposal total concentrations and leachate levels can be compared to background levels. In chapter 6.3 it is concluded that total concentrations in the ashes are higher than natural levels in soils for most elements. For As, Co, Cr and Ni the differences are about one order of magnitude. For Cd, Cu Hg, Pb and Zn the differences are about two orders of magnitude. For filter ash the concentrations of Hg and Cd are even higher.

In Table 8.1, mean leachate levels for the different residues during a period corresponding to L/S 1 are compared to Swedish background levels and guidelines for classification of natural waters regarding metal concentrations (Swedish Environmental Protection Agency).

Table 8.1. Mean leachate levels during leaching to L/S 1 compared to levels in natural Swedish waters.

Levels in water	As	Cd	Cr	Cu	Ni	Pb	Zn
Leachate:	µg/l						
Bed ash ¹⁾	1.2	0.7	180	1.2	9	9	5
Hopper ash ¹⁾	16	0.4	10	4	8	1	5
Bottom ash ²⁾	<9	3	5	<2	6	1	12
Cyclone ash	40	0.2	5	8	40	7	13
Filter ash	600	10	120	7300	400	860000	1400
Background:							
Fresh water	0.3	0.03	1	0.7	3	0.4	3
Classification limits:							
Low level	1	0.05	2	1	5	1	5
Moderately high level	2	0.1	5	2	10	2	15
High level	10	0.3	20	5	50	5	75
Very high level	>10	>0.3	>20	>5	>50	>5	>75
Drinking water:							
According to health	10	1	50	-	-	10	-
Technical standard	-	-	-	50	-	-	300

¹⁾ No end product

²⁾ Leachate levels from CEN L/S 2

For *bed ash* leachate levels of Cd, Cr and Pb can be classified as very high compared to natural waters. For Cd and Pb however, the levels are only about one order of magnitude higher than the limit values for low levels in natural waters, while the level for Cr is two orders of magnitude higher than this limit value. Moreover, the chromium in bed ash leachate is found mainly as Cr(VI) which is regarded as the more toxic form. This type of primary bed ash however, is not disposed of as the main portion is recycled.

There are no classification limits given for salts in the guidelines, but the leachate level of Cl from bed ash is 100-150 mg/l which is about one order of magnitude higher than in fresh water (Borg, 1984).

Most leachate levels from *hopper ash* exceeds the limits for low levels in natural waters by less than one order of magnitude. An exception is As with a level about one order of

magnitude higher. The most pronounced difference compared to natural waters is the chloride level (about 1500 mg/l as a mean value) which is about 15 times higher than normal chloride levels in natural waters. In practice, primary hopper ash is not disposed of separately but constitute a fraction of the bottom ash.

For leachates from *bottom ash*, which is the residue that have to be disposed of (instead of bed ash and hopper ash), only the levels of Cd can be classified as very high. The level of Cr, which is high in leachate from the primary bed ash, is low and comparable with levels from hopper ash. Also for the other elements the bottom ash is comparable to hopper ash.

Cyclone ash is to a great extent similar to bottom ash regarding metal concentrations in leachate. The concentration of As though, is 40 times higher than the low level limit for natural waters. The concentrations of other metals are less than one order of magnitude higher than the low level limits. Probably the leaching of Cl will be the dimensioning factor from the environmental point of view, at least in the short term. The mean leachate level (in the interval L/S 0-1) is found to be about 2000 mg/l, which is about 20 times higher than normal concentrations in natural fresh waters.

The filter ash is completely different compared to the other ash flows regarding leachate levels. Leachate levels from filter ash are considerably higher than from the other ashes, and for some elements several orders of magnitude higher than natural background levels.

From the comparisons with background levels it can be concluded that handling and disposal of bottom ash and cyclone ash should not constitute a severe problem from the environmental point of view. According to the results from the chemical characterization, the ashes are comparable to e.g. ashes from coal combustion and bottom ash from other MSWI facilities. Consequently, landfilling should be possible according to the requirements for such residues. Normally, this implies a landfill with a simple bottom sealing and collection of leachate during the operational stage. After completion, the landfill should be covered with a barrier and a protective cover. Thereafter, collection of leachate will not be necessary. The normal Swedish requirement on the cover for the actual residues is that the mean precipitation shall be reduced to 50 mm a year.

According to the chemical characterization, utilization of bottom ash and cyclone ash may be possible from an environmental point of view. According to Swedish legislation though, utilization have to be applied for in each case taken also the site in question in consideration. No limit values are given for general regulation of utilization.

On the other hand, disposal of filter ash probably will constitute a problem from the environmental point of view. The filter ash is comparable to other dry and semidry APC residues from MSWI and the leaching of salts as well as trace element is considerable. This implies that a very qualified landfill is required for disposal. An alternative is treatment of the ash prior to landfilling either by washing or by stabilization/solidification in order to reduce the leaching.

8.3. The Netherlands

The Netherlands is using column tests at L/S 1 in order to determine if a material is within the limits required for deposition. Below are limiting values for deposition according to C4 and C3. Class C4 denotes household waste or comparable while C3 denotes deposits with

controlled leaching. The category inert deposits does not exist, since inert material is utilized, storage is allowed until treatment can be done. Classes for hazardous waste are also existing (C2 and C1)

Table 8.2 Limits for leached amounts (μ g/kg) at L/S 1 for deposits compared to inert material.

Element	Inert	C4	C3
As	10	8000	8000
Cd	0.4	50	200
Co	10	1000	4000
Cr	50	30000	30000
Cu	20	8000	10000
Hg	0.1	80	80
Pb	40	4000	25000
Mo	1	10	600
Ni	20	8000	10000
Sb	1	100	600
Sn	2	20	1500
Sr	10	1000	5000
Zn	70	10000	40000

The concentrations of Pb in the filter ash of the present material goes beyond the limit for deposition according to these classes and filter ash consequently has to be considered a hazardous waste. The hopper and cyclone ashes are within the limits for deposition, but cannot be considered as inert because of high concentrations of Hg and As, and for cyclone also Co and Ni. Column tests were not performed on the bottom ash, but from the results in batch tests it is likely that it should be classified in the same way as hopper ash. Bed ash is within the limits for inert material except for Cd and Cr. For Cd the column tests gives a leached amount of 0.7 μ g/kg, while the limit value is 0.4.

For the utilization of materials further restrictions are posed. It requires a test procedure involving column tests at L/S 10 and restrictions are also set according to the total content of the material.

8.4. Switzerland

Combustion is recommended for all material that cannot be recycled or utilized in other ways. Three types of deposits are possible for material that cannot be utilized:

- Inert deposit, may contain primarily silicates, carbonates and material similar to normal soil or rock, with low content of trace elements.
- Deposits for residues, that may contain higher concentrations of soluble material and metals.
- Reactor deposits, where waste can be put without fulfilling criterias for final storage. This is partly a treatment method

Classification of waste is based upon total amounts, soluble parts and leachable amounts. The leaching tests are not comparable to the present tests, and no comparison will be done. For inert deposits the limiting values (total concentrations) for Pb, Cd, Cu, Ni, Hg, Zn (Fällman and Hartlén 1993) is stated. None of the ashes fulfils the total concentration criteria for inert deposits.

8.5. Germany

In Germany classification is done according to a batch leaching test, DIN 38414, in this report simply referred to as the DIN-test. A limiting value is based on 20 chemical parameters. A comparison between the obtained leaching results and the limiting values are shown in table 8.3. Limiting values are taken from TA Abfall (1991) and TA Siedlungsabfall (1993)

Table 8.3 *Limit values in Germany compared to results from the DIN-test*

Element	Unit	Bottom ash	Bed ash ¹⁾	Hopper ash ¹⁾	Cyclone ash	Filter ash	Limit values ²⁾	Limit values ³⁾
pH		9,8	10.6	9.9	10.9	12.8	4-13	5.5 - 13
Cond.	mS/m	110	32	133	425	4,200	10,000	10,000
TOC ⁴⁾	mg/l	1,2	<1	<1	<1	15.3	200	20
Phenol	mg/l	-	<0.024	0.032	<0.082	0.023	100	0.2
As	mg/l	<0.0045	0.02	<0.0065	<0.045	<0.3	1	0.2
Pb	mg/l	0.004	0.0017	0.0015	0.0028	101.6	2	0.2
Cd	mg/l	0,0009	0.0002	0.0004	0.0006	0.0035	0.5	0.05
Cr (VI)	mg/l	<0,02	0.265	<0.02	<0.02	<0.02	0.5	0.05
Cu	mg/l	<0,001	<0.001	<0.001	<0.01	4.86	10	1
Ni	mg/l	0,0024	<0.0005	<0.0005	<0.04	<0.2	2	0.2
Hg	mg/l	<0,0003	<0.0002	<0.0002	<0.0004	<0.003	0.1	0.005
Zn	mg/l	0,006	0.0018	0.0044	0.0248	6.14	10	2
Fluoride	mg/l	<1	0.225	<0.1	0.22	3.2	50	5
Ammonium	mg/l	0,11	0.01	0.02	0.19	4.4	1,000	4
Chloride	mg/l	100	12	155	1,100	13,500	10,000	-
Cyanide	mg/l	<0,01	<0.01	0.015	0.02	0.31	1	0.1
Sulphate	mg/l	137	22	130	9	2,050	5,000	-
Nitrite	mg/l	0,33	0.004	0.008	0.012	0.19	30	-
AOX	mg/l	<0,02	0.116	<0.02	0.063	0.103	3	0.3
TDS	%	0.88	0.15	1.25	4	34.4	10	3

¹⁾ No end product

²⁾ TA Sonderabfall

³⁾ TA Siedlungsabfall (Landfill Class I)

⁴⁾ The laboratory has reported disturbances occurring in the TOC-analyses

The bottom ash and hopper ash fall within the limits for TA Siedlungsabfall Deponieklasse I (Landfill Class I). The cyclone ash is exceeding the limit for Deponieklasse I for TDS, probably due to the high concentrations of chloride, although a specific limit for chloride is not present for the Landfill Classes, but falls within Deponieklasse II (TDS<6 %).

The filter ash is exceeding also the Class II limits, factors given within parenthesis, for the following parameters: Pb (100), Zn (1.2), and soluble parts (6) and are close to the limit for Cu and cyanide. Compared to Class I limits, the filter ash fails also for conductivity, As, Cu,

ammonium and cyanide. Furthermore, the limits for Class TA Sonderabfall (Landfill hazardous waste) that represents a more rigorous handling procedure are exceeded (with factors within parenthesis) for the filter ash: Pb (50), chloride (1.3), and soluble parts (3.5).

8.6. Belgium

In Belgium the same test is used to define limit values for 18 parameters (Ye et al. 1995). The bottom ash fall within the limits for utilization. The content of chloride in the cyclone ash are too high to permit utilization. The concentrations of As, heavy metals (= Pb, Cd, Cr, Cu, Ni, Hg, Zn lumped together), chloride, sulphate and cyanide are too high to permit utilization of the filter ash.

8.7. France

In France, the batch test AFX 31-210 is used for classification of ashes. Limiting values is defined for 9 parameters (Table 8.4). Bottom ash, hopper ash and cyclone ash are within the limits for the French classification for utilization, type V. The filter ash exceeds the class V limits for TDS, As, sulphate, and, most significant, Pb by a factor of 180.

Table 8.4. Limit values in France compared to results from the AFX-test

Element	Unit	Bottom ash	Bed ash ¹⁾	Hopper and Cyclone ash ²⁾	Filter ash	Limit values type V
Organic content	%	0.09	<0.1	<0.3	0.02	5
TDS	%	1.1	0.7	4.3	48	5
Cr(VI)	mg/kg	<0.6	3.7	<0.8	<0.6	1.5
Pb	mg/kg	0.1	0.01	0.3	1725	10
Cd	mg/kg	0.01	<0.002	0.006	0.06	1
As	mg/kg	0.1	0.5	0.07	2.6	2
Hg	mg/kg	<0.008	<0.007	<0.05	0.03	0.2
SO ₄ ²⁻	mg/kg	2 500	1 100	900	40 000	10 000
TOC	mg/kg	<30	<30	<30	210	1 500

¹ No end product

² Mixture of hopper ash (1/3) and cyclone ash (2/3)

8.8. USA

The leachability of waste is in USA based on TCLP-tests. The criteria for maximum permissible leached amounts includes several specific organic contaminants and inorganic constituents, metals; As, Pb, Cd, Hg, Ba, Ag, and Se. The proposed criteria for utilization and deposition of cement stabilized wastes, consist of two classes of utilization and two classes of deposition and are also including parameters concerning the hydraulic properties and physical stability of the waste. The present regulatory limits for deposition is exceeded only for lead in the filter ash.

8.9. EC

Within the European Community criterias for waste deposition are presently discussed. A proposal for limiting values based on the batch leaching test DIN 1993 is rejected and currently no proposal is available.

9. UTILIZATION

9.1. General

From an environmental point of view, the quality of the different ashes from fluidized bed combustion (Lidköping plant), as determined in this study, can be favourable when it comes to the potential for utilization, at least for the bottom ash and possibly for the cyclone ash. Generally, the leached amounts of certain critical elements are lower for ashes from the Lidköping plant compared to typical values for ashes from mass-burn plants, cf. the comparison in chapter 7. From chapter 8 it is obvious that utilization of bottom ash in certain countries, e g France, would be accepted according to current limit values. In other countries, e g Sweden, no general limit values are given and utilization have to be applied for in each case. The judgement is then based not only on total contents in the residue and its leaching behaviour but also on the specific environmental conditions at the site.

Bottom ash and cyclone ash are of primary interest for utilization. Theoretically, also hopper ash can be of interest as it is possible to obtain hopper ash separated from the bottom ash. The bed ash is not of interest as it is recycled in the plant. Filter ash show completely different properties from the environmental point of view and must be deposited in some way.

With the available information from the characterization of the different ashes within this project, some different fields of utilization are possible, such as

- fill material (bottom ash and cyclone ash)
- binding agent in cement and concrete (hopper ash and cyclone ash)
- ballast material in concrete

It is of paramount importance to determine the variability of different critical parameters in order to fully evaluate possible fields of utilization of the ashes. This has not been done within this project.

9.2. Fill material

The hopper ash is shown to have a significantly lower grain density ($\rho_s \approx 1.8 - 1.9 \text{ t/m}^3$) than the other ash types which indicates the possibility of using the hopper ash as a light weight fill material. Light weight fill materials are interesting for different kinds of construction purposes in order to improve stability conditions or to reduce settlements.

The minimum bulk density was determined for dry hopper ash (gross sample/full load). A sample container was vibrated slightly while dry ash was slowly poured into the container. This procedure is thought to reasonably simulate field conditions. The bulk density

determined in this way was $\rho = 1.3 \text{ t/m}^3$. To achieve the low bulk density in field compaction and still receive a good compaction result, it is probably favourable to use light weight vibrating rollers. It should also be noticed that the uniformly graded grain size distribution of the hopper ash may constitute an obstacle for its use as construction (embankment) material.

Bottom ash (including the coarse fraction of the bed ash) is medium graded and from this point of view more suitable for utilization. Compaction tests (modified Proctor) on this material showed a maximum density of $1.8\text{-}1.9 \text{ t/m}^3$. Consequently the mixture is not suitable for light weight fills, despite the content of hopper ash with low grain density. This can be explained by a good compaction result in combination with some crushing of aggregates due to the applied compaction method. To achieve a good compaction result without crushing of aggregates it is probably favourable to use light weight vibrating rollers. The grain size distribution of bottom ash does not meet the requirements for qualified road construction materials such as base course gravel, but can probably find its use as ordinary fill material in applications where sand and similar natural materials are used.

It would also be possible to add cyclone ash to the bottom ash in order to obtain an even better graded material. Preliminary studies show that a mixing of hopper ash and cyclone ash will contain a relatively high content of fines which disables its use for construction purposes.

9.3. Binding agent in cement and concrete

A possible field of utilization for the hopper ash and the cyclone ash is as a binding agent in cement and concrete. It is not possible with the prevalent data to definitely conclude whether this is possible or not, even if there are several strong indications pointing in this direction.

Comparing some of the specifications given in BS3892 Part 1 *Pulverized-fuel ash. Specification for pulverized-fuel ash for use with Portland cement* with experimental data for the hopper ash and the cyclone ash gives the following result:

	Criteria	Hopper ash	Cyclone ash	Criteria fulfilled	
				Hopper	Cyclone
Natural water content	< 0.5 %	< 0.5 %	< 0.5 %	x	x
Content of fines	Max. 12 % retained on 45 μm sieve	$\approx 3 \%$	$\approx 30 \%$	x	
Compact density	> 2.0 t/m^3	$\approx 1.85 \text{ t/m}^3$	$\approx 2.4 \text{ t/m}^3$		x
Cl ⁻	$\leq 0.1 \%$	0.24 % ²	1.07 % ¹		
CaO	$\leq 10 \%$	7.8 %	18.2 %	x	
LOI	$\leq 6 \%$	0.08	0.3	x	x

²As determined from availability tests.

It can, thus, be concluded that neither the hopper ash, nor the cyclone ash comply with all specifications given in this standard.

If the same type of comparison is done for BS3892 Part 2 *Pulverized-fuel ash. Specification for pulverized-fuel ash for use in grouts and for miscellaneous uses in concrete* the following result is obtained:

	Criteria	Hopper ash	Cyclone ash	Criteria fulfilled	
				Hopper	Cyclone
Natural water content	< 0.5 %	< 0.5 %	< 0.5 %	x	x
Content of fines Grade A	Min. 12.5 % and max. 30 % retained on 45 µm sieve	≈ 3 %	≈ 30 %		x
Content of fines Grade B	Min. 30 % and max. 60 % retained on 45 µm sieve	≈ 3 %	≈ 30 %		x
MgO	≤ 4 %	1.3 %	2.9 %	x	x
LOI Grade A	≤ 7 %	0.08	0.3	x	x
LOI Grade B	≤ 12 %	0.08	0.3	x	x

The cyclone ash complies with the specifications listed in the table above. It should, though, be noticed that other criteria are applied as well, but the result is a strong indication that the cyclone ash could be used according to the specifications given in this standard.

Carrying out the same type of comparison for BS6610 *Specification for pulverized-fuel ash cement* gives the result:

	Criteria	Hopper ash	Cyclone ash	Criteria fulfilled	
				Hopper	Cyclone
Cl ⁻	≤ 0.1 %	0.24 % ³	1.07 % ²		
CaO	≤ 5 %	7.8 %	18.2 %		
SiO ₂	≥ 25 %	63.7 %	40.4 %	x	x
LOI	≤ 5 %	0.08	0.3	x	x

³As determined from availability tests.

Even if the problems with the high content of Cl^- could be overcome by washing of the ashes, still the content of CaO remains too high to meet the given specifications.

A similar comparison for ASTM C618 *Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete* renders the following result:

	Criteria	Hopper ash	Cyclone ash	Criteria fulfilled	
				Hopper	Cyclone
Natural water content	< 3 %	< 3 %	< 3 %	x	x
Content of fines	Max. 34 % retained on 45 μm sieve	\approx 3 %	\approx 30 %	x	x
$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$	\geq 70 % (N, F)	82 %	67%	x	
	\geq 50 % (C)			x	x
LOI	\leq 10 % (N, F)	0.08	0.3	x	x
	\leq 6 % (C)			x	x

Almost all criteria are fulfilled for both the hopper ash and the cyclone ash. However, there are additional criteria for parameters that have not been determined in this project.

The norm NEN-EN450 *Vliegas voor beton. Definities, eisen en kwaliteitsbeheersing* from the Netherlands gives the following result carrying out the same kind of comparison:

	Criteria	Hopper ash	Cyclone ash	Criteria fulfilled	
				Hopper	Cyclone
Natural water content	< 3 %	< 3 %	< 3 %	x	x
Content of fines	Max. 40 % retained on 45 μm sieve	\approx 3 %	\approx 30 %	x	x
SiO_2	\geq 25 %	63.7 %	40.4 %	x	x
CaO	\leq 1.0 % ⁴	7.8 %	18.2 %		
Cl^-	\leq 0.1 %	0.24 % ⁵	1.07 % ⁴		
LOI	\leq 5 %	0.08	0.3	x	x

⁴A content of CaO of up to 2.5 % can be accepted, provided that the fly ash complies with the given requirement for soundness.

⁵As determined from availability tests.

Once again, the limitations caused by the high Cl⁻ content can be overcome by treating the ashes, e.g. washing. The high content of CaO, though, disables the use of the ashes according to this norm.

Praxis in Sweden is not to replace a certain amount of the cement with e.g. fly ash, even if there are specifications for so called modified standard Portland cement, which can contain 5-10 % fly ash, exclusively from the incineration of coal. However, the operational conditions for coal combustion facilities have changed during the last years, due to more strict environmental legislation, resulting in an uneven quality of the ashes with respect to their potential use in cement. The main difference is that the content unburned matter has increased. It is common that Swedish cement industries nowadays refuse to add fly ash to their product.

9.4. Ballast material in concrete

In Sweden, only natural materials can be used as ballast materials in concrete. In principal can also artificial materials, such as ashes and slags, be used as ballast material. It must, however, be shown that the use of a certain residue does not alter the properties of the concrete either in the short term or in the long term. Staff at the Cement and Concrete Research Institute in Stockholm do not think that there is any potential today for using ashes or slags as ballast material in concrete. They are for the time being running projects using certain residue products, however not ashes or slags from MSWI, to replace a minor amount of the natural ballast material. Several tests have been carried out during many years and they estimate that the project will continue for many years.

10. REFERENCES

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