Technical University of Denmark

Waste incineration bottom ashes in Denmark

Status and development needs by 2003

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affald danmark

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Environment & Resources DTU

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Preface

This white book on bottom ashes from waste incineration was completed in the spring 2003 by Environment & Resources DTU (Technical University of Denmark) in collaboration with major stakeholders related to waste incineration bottom ashes in Denmark. The white book outlines the existing Danish knowledge on bottom ash quality with focus on the Danish regulations, the technical possibilities of upgrading the bottom ash quality, and bottom ash management. The overall objective is to summarize recent experiences gained in Danish research and development projects, and thereby to establish a common ground for identification of needs for further development.

The white book contains an outline of the main problems and issues related to bottom ash management in Denmark, and short summaries of major completed or ongoing projects in Denmark. A number of the projects were briefly presented on a workshop at Environment & Resources DTU in May 2003, and a draft version of this document was discussed among the participants. The white book was later revised according to the inputs given at the workshop.

Preparation of the white book and arrangement of the workshop was initiated by the Danish organization *affald danmark*, and financially supported by the waste incinerators I/S Vestforbrænding, I/S Amagerforbrænding, Elsam A/S Affald og Energi, Århus Kommunale Værker, and I/S Reno-Nord. The steering committee comprised of Kirsten Bojsen (chairman, I/S Vestforbrænding), Uffe Juul Andersen (I/S Amagerforbrænding), Frits Unold (Elsam A/S Affald og Energi), and Thomas H. Christensen (Environment & Resources DTU). Thomas Astrup (Environment & Resources DTU) acted as secretary for the committee and performed most of the work related to the white book.

Copenhagen, September 2003

Kirsten Bojsen
I/S Vestforbrænding
Chairman of the steering committee

Preface to the English version

The white book was edited into English and adapted to a more international audience. The text was revised in order to avoid specific references to Danish conditions that were implicitly understood by the Danish stakeholders. As a consequence, very detailed conclusions derived from specific projects were left out if extensive explanation was required for non-Danish readers to appreciate these conclusions. The Danish version contained rather detailed project summaries provided by the individual project managers. In the English version these summaries were considerably shortened and homogenized in order to provide an easy overview of the projects; for further information, readers are encouraged to contact the individual project managers.

The aim with the English version was to provide plant owners, industry, researchers and authorities in other countries with an introduction to the activities in Denmark regarding bottom ash processing and treatment, and to illustrate the kind of environmental aspects considered and evaluated in Denmark.

Copenhagen, January 2005

Thomas Astrup
Environment & Resources DTU
Technical University of Denmark

Summary and conclusions

Within recent years, a number of research and development projects have been initiated in Denmark with the aim of developing pretreatment options for improving bottom ash quality, and possibilities for reutilization. This white book summarizes the experiences from 20 major projects, and discusses the results in a broader perspective. Further, the white book describes the state of knowledge in Denmark and identifies the most important areas for future development.

The projects discussed here mainly focus on the following aspects:

- Sampling and sample characterization
- Curing
- Washing, with and without additives
- Leaching
- Size fractionation
- Separation of metals
- New reutilization options
- Plant design and operation

The projects have provided us with significant new insight regarding the bottom ash quality and the possibilities for improvement with respect to reutilization. The main conclusions are summarized below.

- Due to the solid composition of bottom ashes, no ashes may be categorized according to category 1 of the Danish statutory order on reutilization of residues.
- Most bottom ashes may, perhaps after extended curing, be pretreated in order to observe the limit values in category 3.
- In most cases, bottom ashes need extensive pretreatment in order to observe the limit values in category 2 for all parameters. It is primarily the leaching of sulfate, Cr and Cu that give rise to problems. In some cases also the leaching of As, Cd, Ni and Pb may be critical. Although, pretreatment may not sufficiently lower leaching of all elements, it is found that leaching reasonably close to the limit values is obtainable. It should be noted that

some bottom ashes may readily, typically after curing, observe the leaching criteria in category 2.

- Significant variations in bottom ash quality have been observed, both between different plants and over time for a single plant. This means that conclusions made within a specific project may not necessary hold on a general level.

- The most promising pretreatment method investigated includes controlled curing and washing with additives such as HCO_3 or CO_2. It should be noted that no specific level of improvement can be guaranteed with respect to leaching. Further pilot or full scale demonstration is necessary.

- An optimal combination of curing and bottom ash washing requires better understanding of the geochemical changes in the ashes.

- It is estimated that even with optimal ash pretreatment, some plants will not be able to reutilize bottom ashes according to the criteria in category 2.

- It is suggested that relevant environmental assessment tools are developed in order to improve the authorities handling of cases involving specific reutilization projects not sanctioned according to category 2 and 3.

- In Denmark, road deicing release considerable amounts of salts into the nearby groundwater. It is suggested that the relatively strict leaching criteria for Na, Cl and sulfate should be reconsidered with respect to bottom ash reutilization in road construction.

- Reutilization according to category 2 imply less environmental impact than according to category 3; however, in both cases the current Danish legislation characterizes the area as a contaminated site after reutilization. As such, the Danish regulation lacks incentives for upgrading the bottom ashes from category 3 to category 2.

- It is suggested that environmental assessments of typical reutilization scenarios are performed in order to evaluate the actual migration of contaminants as well as the consequences of pretreatment.

- It is suggested that the importance of plant operation and waste characteristics are evaluated with respect to bottom ash quality.

Based on the above conclusions, the following disposal scenarios have been found likely for Denmark:

Export. Bottom ashes are exported for reutilization in other countries. No needs for further development have been identified.

Status quo. Bottom ash handling and utilization are continued as today. Development of environmental assessment tools is necessary.

Optimum quality. Bottom ashes are handled and pretreated in order to obtain the best possible quality using washing and curing. In addition to the development needs mentioned above, further development on specific pretreatment techniques is necessary.

New reutilization options. Bottom ashes are pretreated to the required level and reutilized in new applications. Further development of potential reutilization options is necessary.

Revision of legislation. Supplementary to the above scenarios (except the export scenario), the limit values related to category 2 and category 3 reutilization options are reconsidered with respect to the likely environmental impacts. Environmental assessments of specific reutilization scenarios need to be performed.

Contents

Chapter 1

Introduction

1.1 Objectives

The statutory order *no. 655 of June 27, 2000 from the Danish Ministry of Environment and Energy on recycling of residual products and soil in building and construction work* was set into force by January 1, 2001. This had the effect of categorizing bottom ashes in a new manner and putting focus on the leaching properties of bottom ashes. As a consequence, the reutilization options were limited and the demands for pretreatment before reutilization were increased.

In order to meet these new demands, investigations were initiated in connection with the preparations for the statutory order by plant owners and other organizations. These investigations have contributed to a significantly improved understanding of the possibilities for bottom ash treatment and reutilization.

In order to utilize the experiences provided by these investigations as best as possible, it has been necessary to create an overview of the available knowledge, and to point out the areas that need further development. The white book aims to fulfill this function.

1.2 Scope

The overall aims of plant owners are to generate bottom ashes of good quality from an environmental point of view, and to ensure proper reutilization of the ashes.

The way of categorizing bottom ashes by solid composition and leaching properties according the the statutory order has been a central focus point for most development projects. As a consequence, a major part of the discussions throughout this white book is related to the statutory order regulating the reutilization in Denmark. This may, however, not be interpreted as the plant owners want to limit development to the scope of the statutory order.

The white book focuses on the situation in Denmark, solely. Foreign investigations are not discussed, but are briefly mentioned in cases when a Danish project has been directly related to a foreign investigation.

In this work, bottom ashes are interpreted as the solid residue that is removed from the end of the grate at municipal solid waste incinerators. Bottom ashes may have varying contents of grate siftings and boiler ashes. In this white book, *bottom ashes* are—relative to the context—used to describe either fresh ashes as removed from the incinerator, or pretreated and cured bottom ashes ready for reutilization.

Chapter 2

Current Status

2.1 Bottom ash generation

Figure 2.1 shows annual amounts of bottom ashes generated at Danish waste incinerators as registered by the Danish EPA in the period 1995–2001 (DEPA, 2002). About 500,000 tons are removed from the plants annually. These amounts correspond to a yearly increase in the waste quantities incinerated: an extra 1 million tons of waste was incinerated in 2001 compared with 1995. This may indicate that less non-burnable waste fractions were accepted at the incinerators.

Between 1995–2001, bottom ash reutilization has been relatively stable at about 400,000 tons annually, corresponding to about 75–87 % of the bottom ashes generated. In the same period, an average of 180 kg bottom ash has been generated per ton of waste incinerated.

2.2 Solid composition and leaching properties

It should be realized that the solid composition of bottom ashes, and also the leaching properties, depends on a large number of parameters such as: type and composition of the incinerated waste, plant design and overall mode of operational, detailed conditions on the grate, ash handling and processing as well as conditions during the time of curing.

An almost endless number of possible variations in these parameters exists, but bottom ashes nevertheless appear as a material with relatively well defined properties, at least from a technical point of view. Table 2.1 shows typical contents of selected elements in bottom ashes from I/S Vestforbrænding. It can be noted that some of the elements show significant variations, e.g. Pb, As, Cd, Cr, Hg, and Ni. Figure 2.2 illustrates variations in Pb content in bottom ashes from I/S Vestforbrænding in the period 1993–2001. Here, it can be seen that the actual measured Pb content vary up to about 5 times in the period; however, it should be realized that this variation includes uncertainties introduced during sampling, sample handling and processing, and analysis.

Leaching data also show considerable variation, even greater than what is seen for the solid composition data. In most cases, very high leaching of salts

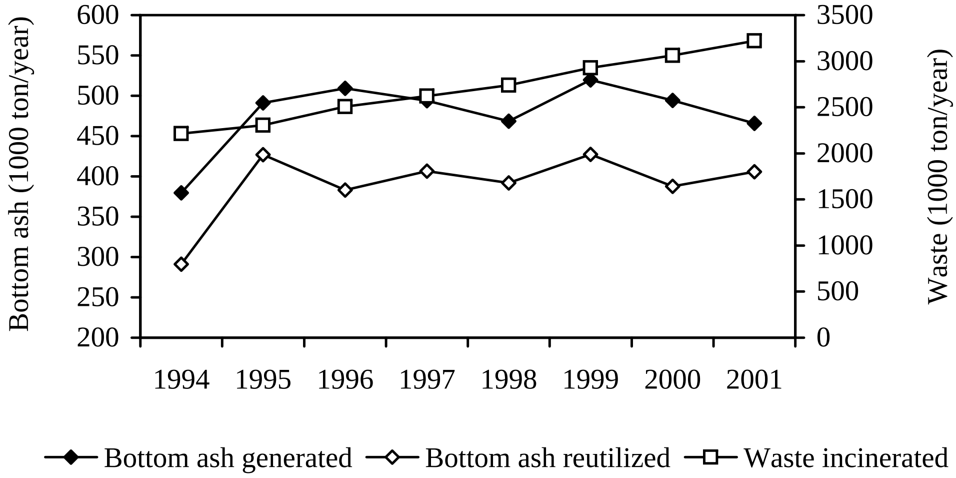

Figure 2.1: Waste quantities incinerated as well as bottom ash quantities generated and reutilized in the period 1994–2001 (Danish EPA, 2002).

Table 2.1: Solid content of selected elements in bottom ash samples from I/S Vestforbrænding between 1993–2001.

		Interval	Average	Relative uncertainty	No. of samples
pH		9.9–11.1	10.6	2 %	107
Alkalinity	meq/kg	1.8–3.8	2.9	17 %	94
LOI	%	0.2–3.8	1.7	46 %	88
Al	g/kg	45.0–56.1	50.3	11 %	21
Ba	g/kg	1.1–2.4	1.5	4 %	4
Ca	g/kg	89.1–104	94.9	8 %	21
Fe	g/kg	46.7–77.8	65.1	21 %	21
K	g/kg	7.4–8.6	8.1	7 %	21
Mg	g/kg	10.5–11.2	10.7	3 %	21
Mn	g/kg	0.9–1.0	0.9	5 %	4
Na	g/kg	33.3–39.2	35.4	7 %	4
Cu	g/kg	3.4–11.0	5.6	28 %	21
Zn	g/kg	2.0–4.8	3.1	29 %	21
Pb	g/kg	0.6–2.6	1.4	34 %	106
As	mg/kg	7.6–24	14.5	81 %	21
Cd	mg/kg	1.0–12.0	2.7	66 %	105
Cr	mg/kg	57–352	113.9	81 %	21
Hg	mg/kg	0.01–0.62	0.11	74 %	107
Ni	mg/kg	73–390	138	57 %	21

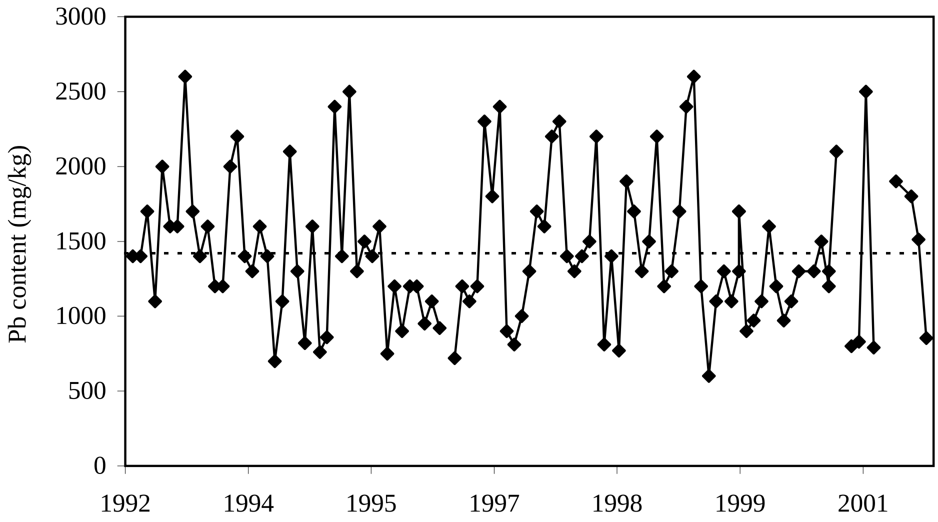

Figure 2.2: Variations over time in Pb content in bottom ashes from I/S Vestforbrænding in the period 1993–2001.

like Cl, Na, Ca, K, and SO_4^{2-} can be observed. Typically, the leaching of heavy metals is more moderate although some metals can be leached in relatively high concentrations (see typical values in Table 2.2).

The relative amount of heavy metals that may be removed from the solid phase in the most common leaching tests (like batch tests at liquid-to-solid (L/S) ratios of 2 l/kg or 10 l/kg) is very small, typically less than one percent. The amount of salts that can be released in leaching tests is usually much higher, typically up to 30–100 %. Often, the maximum fraction of heavy metals that is available for leaching amounts to a few percent. It should be noted that only in very few cases it has been possible to observe a meaningfull correlation between the solid content of heavy metals and the leaching determined in a leaching test on a specific bottom ash sample. This is most likely caused by the very complicated chemical properties of bottom ashes, and the fact that a range of solution parameters affect the leaching, i.e. pH, solubility, complexing, sorption, etc. As such, the release of a specific heavy metal is affected by the presence of other elements and minerals in the solid phase. The leaching of salts, on the other hand, are mostly controlled by the availability and are therefore more related to the solid content than heavy metals.

Salts like Cl and Na may be completely depleted even at low L/S ratios of about 2–10 l/kg, while heavy metals and low soluble minerals, e.g. silicates, may continue leaching for up to L/S ratios above 1000 l/kg. Bottom ashes have a very porous structure with a large fraction of internal surface area which may delay and hamper the exchange of elements between the solid phase and the leaching solution.

Table 2.2: Leaching of selected elements at L/S 2 l/kg for 26 bottom ash samples from Odense Kraftvarmeværk in the period 2001–2002.

		Interval	Average	Relative uncertainty
pH		8.6–11.6	11	8 %
Conductivity	mS/cm	3.99–7.09	5.4	18 %
Cl	mg/kg	780–3200	2000	28 %
SO_4^{2-}	mg/kg	240–4000	1840	57 %
Na	mg/kg	240–7800	1590	85 %
Ca	mg/kg	180–1500	560	79 %
As	μg/kg	4.0–28	15	42 %
Cd	μg/kg	0.3–1	0.4	47 %
Cr	μg/kg	20–700	190	100 %
Cu	μg/kg	500–4000	2100	51 %
Ni	μg/kg	4.8–24	12	38 %
Pb	μg/kg	2–110	12	190 %
Zn	μg/kg	2–180	40	95 %

2.3 Current legislation

Background

Reutilization of bottom ashes in Denmark is regulated by the statutory order no. 655 of June 27, 2000 on recycling of residual products and soil in building and construction work (Ministry of Environment and Energy, 2000). The work leading to the statutory order was initiated by mid 1990's and has included several evaluations of the possibilities of using leaching related criteria values for regulating the reuse of soil and residues (e.g. Hjelmar et al., 1998). The Danish incinerators have been deeply involved in this process as sparring for the Danish EPA, and have participated in the work represented by the organizations: Affaldsteknisk Samarbejde, affald danmark, and DAFONET.

The final basis for determining the limit values related to leaching is described by the Danish EPA in report no. 467-1999 (Dahlstrøm and Rasmussen, 1999). Based on accepted groundwater quality criteria and typical background concentrations of interest, a number of disposal scenarios was modeled in order to determine the maximum allowed concentrations of selected elements in leachate from bottom ashes as measured in an L/S 2 l/kg batch test.

Allowed reutilization options

In the statutory order, building and construction works are understood as the construction of roads, pathways, squares, parking spaces, embankments, dikes, railroad foundations, harbor constructions, and fillings under floors and in building foundations. Al reutilization not regulated by this statutory order must be done in accordance with the Environmental Protection Act (Ministry of Environment and Energy, 2001).

Table 2.3: Limit values for the solid composition and the leaching properties. Values for the solids in category 2 and 3 are identical. Values for leaching in category 1 and 2 are identical. Ministry of Environment and Energy (2000).

Solids		Category 1	Category 2	Category 3
As	mg/kg	0–20	>20	
Pb	mg/kg	0–40	>40	
Cd	mg/kg	0–0.5	>0.5	
Cr-total	mg/kg	0–500	>500	
Cr(VI)	mg/kg	0–20	>20	
Cu	mg/kg	0–500	>500	
Hg	mg/kg	0–1	>1	
Ni	mg/kg	0–30	>30	
Zn	mg/kg	0–500	>500	
Leaching		**Category 1**	**Category 2**	**Category 3**
Cl	mg/l	0–150		150–3000
SO_4^{2-}	mg/l	0–250		250–4000
Na	mg/l	0–100		100–1500
As	µg/l	0–8		8–50
Ba	µg/l	0–300		300–400
Pb	µg/l	0–10		10–100
Cd	µg/l	0–2		2–40
Cr	µg/l	0–10		10–500
Cu	µg/l	0–45		45–2000
Hg	µg/l	0–0.1		0.1–1
Mn	µg/l	0–150		150–1000
Ni	µg/l	0–10		10–70
Zn	µg/l	0–100		100–1500

The statutory order introduces three categories that soil and residues are grouped according to depending on their solid composition and leaching properties, see Table 2.3. Residues in category 1 may be reutilized for building and construction purposes covered by the statutory order without further permission. Residues in category 2 and 3 may only be reutilized for special purposes as summarized in Table 2.4. Waste incineration bottom ashes cannot be placed in category 1 due to their solid content. Reutilization in category 2 and 3 involves placing the bottom ashes above the groundwater level and more than 30 m from the nearest drinking water supply well. Bottom ashes may only be stored on-site without cover for up to 4 weeks, and with cover for up to 6 months.

Sampling and testing

The statutory order requires that at least 50 samples of 2 kg each should be taken and mixed to one sample of 100 kg. This should be done from every lot of 5000 tons. The actual sampling technique is not specified. The 100 kg sample should be screened at 45 mm, and large particles should be crushed and screened

Table 2.4: Overview of reutilization options allowed in category 2 and 3 (Ministry of Environment and Energy, 2000).

	Category 2	Category 3
Roads	Firm top layer,[a] h max. 1 m	Sealed surface,[b] h max. 1 m
Pathways	Firm top layer, h max. 1 m	Firm top layer, h max. 1 m
Squares	Firm top layer, h max. 1 m	-
Cable trenches	Firm top layer	Firm top layer
Ramps	Firm top layer, h max. 4 m	-
Sound absorbing walls	Firm top layer, h max. 5 m	-
Foundations, floors	h max 1 m[c]	h max 1 m[c]

[a] Asphalt, concrete, tiles, min. 1 m of category 1 soil.
[b] Asphalt, concrete, etc. and drainage of surface water.
[c] No indoor climate problems.

again. It is allowed to remove non-crushable material. The sample is divided to 5 kg, which is then crushed to below 4 mm. The crushed sample is then divided into two samples; one of these is used for determination of the solid composition and the other for leaching testing. The solid composition is determined based on digestion with HNO_3, and the leaching properties are determined based on an L/S 2 l/kg batch test (CEN, 2002).

Other regulation

The producer of the bottom ashes, i.e. typically the incinerator or a company handling the ashes, needs to provide information like test data, appropriate category, place of origin, type of handling and processing, and testing methods.

Reutilization of bottom ashes requires notification with the regional authorities who may grant exemption for specific restriction in the statutory order. In case of reutilization, the regional authorities are required to register the area where bottom ashes are placed as a possible contaminated site according to the Soil Contamination Act (Ministry of Environment and Energy, 1999). In practice, this means that future utilization of the area are limited and that the regional authorities may place specific conditions relative to future building and construction works on the site.

2.4 Critical elements

In practical, it is the leaching properties of the bottom ashes that determine which category the ashes can be placed in as no limit values are stated in category 2 and 3 for the solid content (see Table 2.3). As previously mentioned, significant variations in bottom ash quality can be observed between incineration plants. This means that different elements may be critical with respect to the limit values

Table 2.5: Leaching data at L/S 2 l/kg for 10 bottom ash samples from 10 Danish incinerators, and the number of samples in each category (Sander, 2002).

			Number of samples		
		Interval	Category 2	Category 3	Outside category[a]
Al	mg/l	<1–200			
Ca	mg/l	100–630			
Cl	mg/l	270–2600	0	10	0
K	mg/l	100–820			
Mg	mg/l	<0.05–0.61			
Na	mg/l	170–1600	0	9	1
SO_4^{2-}	mg/l	130–2100	2	8	0
TOC	mg/l	10–156			
As	μg/l	<5–17	3	7	0
Cd	μg/l	<0.3	10	0	0
Cr	μg/l	3–1600	2	6	2
Cu	μg/l	24–3300	1	5	4
Ni	μg/l	<5–13	7	3	0
Pb	μg/l	1–1300	8	1	1
Zn	μg/l	<10–79	10	0	0
Total			43	49	8

[a] Leaching is above the limit values of category 3.

for ashes from different incinerators. However, certain common features can be found:

- No bottom ashes may be categorized in category 1 due to the solid composition.
- Only in very few cases, bottom ashes may observe the leaching criteria for category 2.
- Most bottom ashes may with the typical handling and processing be reutilized according to category 3; in some cases extended curing may be necessary.

In conclusion, reutilization of bottom ashes in Denmark is limited to the possibilities allowed in category 3. Reutilization according to category 2 will in most cases require a dedicated pretreatment of the ashes. In this context, the leaching of salts (Cl, Na, and SO_4^{2-}) and heavy metals like Cu, Cr, and to some extent As, Ni, Cd, and Pb needs special attention. Table 2.5 gives an example of categorizing ash samples from 10 Danish incinerators.

2.5 Current bottom ash processing

Currently, bottom ash processing in Denmark includes two processes: curing and separation. Often the curing is divided into two with an initial period of 2–8 weeks before separation, and a later curing until reutilization. Separation is often done using a trommel screen with 50 mm openings. The fine fraction from this separation amounts to about 90–95 % by weight. Both fractions are passed by a magnet to remove magnetic particles. In some cases non-magnetic metals are also separated. Large particles are usually crushed and screened again. Non-burned paper and plastics are returned to the incinerator.

Separated iron, copper and aluminum are reutilized while a part of the coarse fraction is landfilled. The fine fraction, i.e. the processed bottom ash, is cured for 2–4 months. Ash samples for characterization are most often taken directly from the bottom ash pile after curing. In some cases, the samples are obtained from a conveyor belt during separation.

2.6 Current bottom ash reutilization

Technical issues

Denmark and some parts of Europe have a strong tradition for reutilization of bottom ashes for construction of roads, parking spaces, etc. From a technical point of view, the bottom ashes have excellent properties and may fulfill the same requirements as virgin materials under specific conditions, e.g. in the case of road construction (see Pihl and Milvang-Jensen, 2002). Important properties with respect to reutilization are particle size distribution, water content, and amount of non-burned material. When used as base layers in roads, special attention should be placed on layer compaction during construction.

Examples of reutilization

Bottom ashes in Denmark has typically been reutilized for the following purposes:

- Base layers used in construction of parking spaces and roads.
- Filler material for construction of harbors, roads and embankments.
- Filler material in construction of foundations under buildings.
- Small projects such as parking spaces, pathways, private roads, etc.

The small projects may involve only a few truck loads of bottom ashes. The amount of ashes used in small projects compared with the larger projects depends on market possibilities, and how ash distribution and marketing is done from the individual incinerators.

The statutory order no. 655 had the effect of decreasing the number of small projects as the site is now registered as contaminated. Now, reutilization mainly occurs in cases where the landowner is not affected by this.

Chapter 3

Research and Development Projects

3.1 Overview

Problems investigated

20 major Danish research and development projects have been identified concerning bottom ash; the projects have all been completed or initiated in the period 1999–2003. The main objectives of the projects have been to provide new insight concerning the possibilities of improving the bottom ash quality and specifically to improve existing pretreatment techniques. Table 3.1 gives an overview of the Danish projects.

Most focus has been given to leaching of elements that are critical with respect to the criteria given in the statutory order on reutilization, i.e. especially sulfate, Na, Cl, Cr and Cu. One objective has been to understand the mechanisms controlling leaching of these elements, and based on this develop techniques to limit this leaching from the treated ashes.

Other issues have been investigated in addition to leaching: sampling and sample handling, methods for ash separation based on grain sizes, methods for sorting out non-magnetic metals, and new promising reutilization options.

Table 3.2 summarizes the main factors investigated in the individual projects. The table illustrates that considerable focus has been given to methods for removing critical elements from the bottom ashes by washing—with and without additives. Also, the effect of removing specific grain size fractions has been investigated with respect to leaching. Issues like ash inhomogeneity and composition variations over time have also been given attention.

It should be noted that some countries—especially Japan—have traditions for thermal treatment of ashes. These technologies have not been investigated in the Danish projects due to the high energy consumption of such technologies. As such, thermal treatment is likely to be less environmentally efficient than washing and curing.

Table 3.1: Overview of major Danish bottom ash projects in the period 1997–2003. The alphabetic characters correspond to the project summaries given in Appendix B.

A	Clinical waste and health issues related to bottom ashes at I/S Amagerforbrænding
B	Bottom ash washing with and without addition of $NaHCO_3$
C	Uncertainties related to bottom ash sampling
D	Development in leaching during storing and curing
E	Demonstration of bottom ash reutilization
F	Ferrox stabilization of bottmo ashes
G	C-RES incineration ash database
H	Bottom ash stabilization using washing, separation and storing
I	Technical and economical evaluation of separation of metals from bottom ashes
J	Bottom ash washing
K	Sorting of grain sizes
L	Bottom ash qualities
M	LCA on bottom ash reutilization in road construction
N	Modeling of leaching from bottom ashes
O	Bottom ash treatment
P	Bottom ash separation
Q	Leaching of Cu and organic matter from bottom ashes
R	Leaching from cement stabilized bottom ashes
S	Marine reutilization of bottom ashes
T	Bottom ash curing, and washing with CO_2

Important relationships

Table 3.3 gives an overview of the investigated treatment options, and qualitatively the resulting effect on leaching of the most critical elements.

It can be seen that most projects show a significant improvement in leaching properties after simple washing, both with respect to salts and heavy metals. The leaching may be further improved by using additives; however, the effect vary with the characteristics of the bottom ashes investigated. It should be noted that less projects have investigated the effect of additives compared with simple washing. Curing shows a significant improving effect on leaching, except that sulfate leaching appears to increase after curing. Removing ash particles with small grain sizes can improve leaching, primarily with respect to sulfate, but most likely also heavy metals.

The following sections will discuss important aspects of the individual projects, and present the main results.

Table 3.2: Overview of topics investigated in the projects A–T.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
Variations/inhomogeneity		x	x	x			x	x												
Sampling & handling			x																	
Analytical uncertainty			x																	
Grain size: total content										x	x			x						
Grain size: leaching			x					x		x	x			x	x					
Leaching tests: type							x												x	
Sample crushing								x							x					
Curing of ash		x		x				x		x					x		x			x
Ash washing: quench tank		x								x										x
Ash washing: externally								x		x					x					
Separation: grain size										x	x				x					
Addition of $NaHCO_3$		x						x							x					
Addition of CO_2								x												x
Addition of Fe-oxider						x														
Organic matter								x							x		x			
Pilot/full scale leaching					x									x						
Plant design & operation										x		x			x					
Health issues	x																			
Separation: metals									x							x				
New disposal options																		x		
LCA perspectives													x							

Table 3.3: Overview of the main treatment methods investigated, and qualitatively their ability to decrease leaching of Cl, Na, SO_4^{2-}, Cr, Cu, Pb, Zn, and Ni (illustrated as the number of projects with either a positive or negative effect).

	Cl / Na	SO_4^{2-}	Cr	Cu	Pb / Zn	Ni
Storing and curing	++++	− − −	++	+++++	+++	(+)
Washing	+++++	+++	++	++++	++	+
Addition of $NaHCO_3$		++/−	+/−		+	
Addition of CO_2		+/−	+/−	+	+	
Addition of Fe-oxider		(−)	+	+	+	+
Removal of fine fraction	+	++			+	

3.2 Sampling, sample handling, and characterization

Objectives

An important prerequisite for characterizing the generated bottom ashes is the possibility of taking samples that are representative of a larger ash quantity. This is important in more than one respect: whether the ashes observe the limit values in question and whether an observed effect of a specific treatment is significant or not.

As discussed in Chapter 2, bottom ashes are very inhomogeneous, both with respect to physical and chemical properties. These inhomogeneities include variations within a specific ash quantity, but also variations over time and between different plants. As a consequence, sampling and the subsequent handling requires special attention.

Experiences

Møller and Pedersen (2001) investigated the uncertainties related to manual sampling, mechanical sampling, and sampling using the "stopped belt" method. Also, the importance of sample handling, especially sample crushing and sample dividing, were studied. Several projects to some degree addressed ash inhomogeneities and variations on lab data. Pedersen and Møller (2003) took samples from three different plants using the "stopped belt" method.

In general, considerable variations on ash composition and leaching were observed for "identical" ash samples; both in the case of manual sampling, and sampling using the "stopped belt" method.

Typically, it was observed that the relative uncertainty on the determination of salt and metal leaching as specified by the Danish statutory order on residues were in the order of 20–100 % (Møller and Pedersen, 2001; Pedersen and Møller, 2003; Skaarup, 2001). Considerable variations were observed on the determination of sulfate, but the largest uncertainties were found on Cu leaching. The most likely reason for this is the binding of Cu to organic matter and changes in organic matter characteristics during curing (Møller and Pedersen, 2001). The degree of curing and the sampling strategy likely have profound importance for determination of Cu leaching. It can be noted that Skaarup (2001) observed a small relative uncertainty (less than 30 %) on determination of the solid content of Cu in nine ash samples taken manually.

Boddum and Skaarup (2002) found that the relative uncertainty related to leaching testing was in the order of 5 % with respect to salt leaching. Uncertainties related to analysis were set to 5–10 % as a typical value. Uncertainties were significantly decreased when samples were crushed before dividing (Møller and Pedersen, 2001).

Conclusions

Characterization of bottom ashes following the Danish statutory order may be linked to considerable uncertainties, and sampling and sample handling may play an important role. For future investigations, it will be useful to have a quantification of the uncertainties related to specific methods for sampling and sample handling.

It is important to realize these uncertainties, especially in development projects with limited resources for sampling and analytical work. The uncertainties related to sampling alone may easily render the effects of a specific treatment insignificant.

3.3 Curing

Objectives

In Denmark, bottom ashes are typically cured for a few months in order to improve the technical properties of the ashes before reutilization. From the point of view of plant owners, a more detailed understanding of the mechanisms occurring during curing is desired in order to improve the bottom ash quality.

The degree of curing most likely vary internally within a bottom ash heap due to variations in leaching and CO_2 uptake. Such variations are important with respect to characterization, including sampling, of the ashes.

Experiences

In general, it was observed that the leaching properties were improved after curing. Several explanations exist:

- Mineralogical and geochemical changes due to CO_2 uptake (carbonation) and pH decrease.
- Dissolution of primary minerals and formation of secondary minerals.
- Binding of dissolved elements to the ash matrix by sorption.
- Removal and transformation of available organic ligands, e.g. by evaporation, leaching, or changes in binding characteristics.
- Leaching of highly dissolvable salts.

Skaarup (2001) investigated leaching from a specific bottom ash heap during curing in 183 days and found that the curing had a dramatic effect on Cu leaching. The effect on leaching of other metals were less profound; maybe except Ni that appeared to decrease with curing time. Generally, a downwards transport of salts and metals in the ash heap was observed. Most projects observed that leaching of metals like Cu, Cr, Pb, and Zn decreased after curing. Similar observations were done for salts like Na and Cl; sulfate leaching was generally observed to increase.

It is evident that the geochemical properties of bottom ashes change during curing for several months (curing for up to about 6–8 months has been investigated), and that these changes are important with respect to leaching. It is generally experienced that curing for 3–6 months result in less leaching of heavy metals and salts; however except sulfate leaching. In some cases Danish bottom ashes are cured for up to 12 months in order to decrease Cu leaching.

Conclusions

The Danish projects have not produced any detailed information about geochemical changes induced by bottom ash curing; on the other hand, the projects have demonstrated important relationships between curing and leaching. Although several investigations on ash weathering and geochemical changes have been completed at an international level (e.g. as referred in Sabbas et al., 2003), more focus on real-life applications and possibilities for optimizing curing under Danish conditions are needed. Specifically, investigations addressing how curing affects the leachability of organic matter.

3.4 Washing, with and without additives

Objectives

Generally, bottom ash washing is viewed as a highly efficient method for upgrading ash quality in Denmark while at the same time minimizing energy and resource consumption. In many projects, washing processes have been investigated in conjunction with the use of additives such as $NaHCO_3$ and/or CO_2 for improving sulfate removal efficiencies. One project utilized Fe-oxides for binding of heavy metals. In all projects, focus has been placed on leaching properties of the treated bottom ashes.

Experiences

A number of projects investigated ash washing either in lab scale (Boddum and Skaarup, 2002; Sander, 2002), in the quench tank (Boddum and Skaarup, 2000; Project B), or in pilot scale washing plants (Boddum and Skaarup, 2000; Project T). Additionally, several projects investigated effects from additives ($NaHCO_3$, CO_2 and Fe(II)).

Overall, significant improvements on the leaching properties were observed in all projects. This was especially the case for salt leaching (sulfate, Cl and Na), but also Cu, and to some extend Cr and Pb were affected. Use of additives did not show similar significant effects. Generally, projects using $NaHCO_3$ and CO_2 (Project B; Boddum and Skaarup, 2002; Sander, 2002; Project T) concluded that improvements on Cl and Na leaching might be related to the washing process rather than the additives.

Most projects observed increased sulfate solubility in the process water by adding $NaHCO_3$ and CO_2 due to the presence of carbonates. However, only a few projects showed a permanent effect in the subsequent leaching test. It was found that sulfate was bound in Ca-Al minerals in the untreated ashes as these elements were released to the process water during washing (Sander, 2002). Generally, it was anticipated that sulfate was bound as gypsum after the washing process, regardless whether or not additives were used.

In some cases, heavy metals like Cr, Cu and Pb showed lower leaching when using additives in the washing process; however, it was unclear whether this was caused by changes in pH. Sander (2002) and Boddum and Skaarup (2002) found that treatment of cured bottom ashes gave better leaching properties compared with treatment of fresh bottom ashes.

Stabilization using Fe(II) primarily had an effect with respect to Pb, but also Cu, Zn and Cr leaching was improved. The main reason was changes in pH and the presence of binding capacity in the form of Fe-oxides (Lundtorp, 2002).

Overall, the experiences related to bottom ash washing and possible effects from additives can be summarized as the following:

- The main improvement in leaching properties is related to washing, both with respect to salts and heavy metals.
- Additional, but less significant, improvements may be ascribed to the additives $NaHCO_3$ and CO_2. Both salts and heavy metals may be affected, but the effect vary greatly between projects.
- Stabilization using Fe(II) generally provides an effective binding of Pb.
- Treatment of cured bottom ashes are generally a better alternative than treating fresh ashes.

Conclusions

The Danish projects have investigated several washing processes, both with and without using additives, but no single treatment process has been found to ensure leaching below the limit values of category 2. However, it has been shown that considerable improvements in leaching properties may be achieved on specific ashes, and that leaching of some elements can be very close to the limit values after treatment. Most problems are related to salts, especially sulfate, as well as Cr and Cu.

Significant variations in the ash quality can be seen, both between projects but also within specific projects. This make comparison among projects difficult, and make it difficult to establish general relationships between treatment and effect on leaching. Only a few projects attempted to quantify whether effects from additives were significant relative to simple washing without additives. In most projects, the bottom ashes used are characterized only by a few parameters. This makes it very difficult to isolate the decisive factor, but illustrates the importance of including a more thorough characterization of the investigated ash samples. Based on the experiences gained in the Danish projects, full scale implementation of washing processes will most likely need to be preceded by a feasibility study in order to optimize the process with respect to a specific bottom ash.

The current understanding of the geochemical processes affecting bottom ashes during washing are not sufficient to solve the problems with leaching of sulfate, Cr and Cu. Also, an improved understanding is needed of how data from specific leaching tests may be related to the conditions during and after ash treatment; the geochemical conditions in the two cases are most likely different.

Although several investigations at an international level have addressed geochemical processes during weathering and full scale curing/disposal, more focus on the geochemical changes during washing is needed. Only one project addresses the importance of kinetics with respect to release of salts and heavy metals to the process water (Project N). In future projects, more focus on kinetic issues during washing is needed in order to fully optimize ash treatment.

3.5 Organic matter

Objectives

For most bottom ashes, a distinctive relationship between dissolved organic matter in the leaching solution and Cu leaching can be observed. Therefore, an understanding of Cu complexation, and changes in composition and properties of the organic matter, during washing and curing is necessary.

Experiences

Several projects observed a correlation between leaching of organic matter and Cu (Project B; Sander, 2002; Boddum and Skaarup, 2002) while other projects did not observe similar relationships (Skaarup, 2001). Generally, curing showed a significant reduction in TOC leaching; this was often correlated with the Cu leaching.

One project (Project Q) performed a more detailed investigation of the relationship between organic matter and Cu leaching. A significant correlation between TOC and Cu leaching was found; both TOC and Cu leaching decreased with the curing time. In this project, the bottom ashes were cured in the lab under moist conditions, but without leachate generation. It was concluded that the decrease in TOC leaching was not caused by removal with leachate, and that microbial degradation did not play an important role. Instead, it was concluded that the decrease was likely caused by evaporation of organic acids and/or immobilization of organic matter during curing. Fractionation of the dissolved organic matter showed that Cu was primarily associated with larger organic molecules, e.g. humic acids.

Sander (2002) found that TOC leaching was decreased to about 20 % after washing of the ashes; Grøn (2003) observed a similar decrease by curing. Similar observations were made by other projects (Project B; Boddum and Skaarup, 2002).

Conclusions

The interactions between organic matter and Cu have mainly been investigated in foreign projects (e.g. Meima et al., 1999) while the Danish projects have focused on documenting relations between TOC and Cu leaching, and showed that specific treatment options, e.g. curing and washing, facilitates improved Cu leaching properties of the treated bottom ashes. The Danish projects supports the fact that organic matter is a key issue with respect to Cu leaching.

In order to provide a basis for further optimization of treatment processes with respect to Cu leaching, it is necessary to perform a review of international investigations focusing on changes in organic matter composition, binding, and quality during washing and curing.

3.6 Size fractionation

Objectives

It is known that heavy metals in the incinerator are condensed on particle surfaces; especially small particles with a large specific surface area. Consequently, it has been tested whether removing small sized particles from bottom ashes could improve the ash quality. In addition to minimizing the heavy metal content and improving the leaching properties, it is desired to improve the technical quality of the ashes for reutilization in building and construction works.

Experiences

Bendz and Flyhammar (Project N) investigated the leaching from specific grain size fractions in order to establish a model describing bottom ash leaching. They found that the specific surface area of ash particles in a given size fraction was the main parameter correlating the release of salts to solution. Further, heterogeneous reactions with internal particle surfaces were found to control the overall release to solution, and solid phase diffusion to be important in the initial part of leaching. They also found that gypsum might control Ca and sulfate concentrations in the leaching solution.

Boddum and Skaarup (2002) investigated in lab scale the effects of removing grain sizes below 125 μm in combination with washing. It was found that sulfate was concentrated in the small grain sized fraction. Generally, the most significant effect with respect to leaching was observed for sulfate, Na, Cr, Mo and organic matter. Using additives in the washing process mainly affected sulfate and Mo.

Boddum and Skaarup (2002) used a soil washing facility to wash the bottom ashes, and found that both heavy metals and salts were concentrated in the particles with grain sizes below 100 μm. It was concluded that an combination of washing and size separation had a positive effect on the leaching of sulfate, As, Cd, Pb and Zn; also the technical properties of the ashes were improved by the treatment.

Project K likewise found that Cl and S were concentrated in particles with small grain sizes while most Cu was found in the gravel fraction. Pb was found in highest concentrations in the sand fraction. For other elements, no significant correlation to grain sizes was observed. The leaching properties of a combined sand and gravel fraction were investigated; although improvements were observed, the salt leaching was still above the limit values. Møller and Pedersen (2001) found that sulfate and Cr were concentrated in particles with grain sizes < 4 mm.

Conclutions

It appears evident that removal of small sized particles also results in removal of salts and heavy metals. It is possible that dissolution of primary mineral phases and precipitation of secondary phases, e.g. gypsum, during washing may further increase the number of small particles containing salts and heavy metals; this will increase the effect of removing these particles.

In projects combining washing with particle removal, it can be difficult to isolate the effects from washing and grain size separation. It is found likely that removal of small sized particles can improve the leaching properties of bottom ashes, but it is necessary to further demonstrate this in pilot scale. Moreover, it is unclear whether solubility control, for example for sulfate, may reduce the effect of removing part of the solid content with the small particles.

3.7 Sorting out metals

Objectives

Traditionally, processing of bottom ashes in Denmark includes separation of the magnetic metals. However, it is desired to evaluate the perspectives for recovering non-magnetic metals also.

Experiences

Project P investigated the potential amounts and qualities of non-magnetic metals recovered from four bottom ashes. Before sorting, the ashes were homogenized by sieving and crushing. Sorting of non-magnetic metals larger than 6 mm were done using air-jets. It was estimated that the recoverable non-magnetic metals amounted to about 0.16–0.45 % of the original bottom ash per weight; the magnetic fraction constituted about 3.6–6.9 % per weight. The quality of the recovered metals was good.

Based on German and Dutch experiences, Project I estimated similar recovery efficiencies based on magnets, eddy-current, and manual sorting.

Conclusions

It has been demonstrated that it is possible to recover both magnetic and non-magnetic metals of a quality sufficient for reutilization. Given the current situation in Denmark, a decision of implementing recovery of non-magnetic metals will most likely be related to the marketing possibilities for bottom ashes without this extra recovery. No projects have investigated possible effects on leaching from sorting out metals from the ashes.

3.8 New reutilization options

Objectives

In order to maintain a high reutilization rate, frequent evaluation of new potential disposal options is necessary. With respect to the limit values in the Danish statutory order on reutilization in building and construction work, a specific need for investigating new market possibilities arose.

Experiences

Five projects focused on ash reutilization and disposal. Crillesen and Hjelmar (Project E), and Bendz and Flyhammar (Project N) investigated leaching from bottom ashes used in road construction. Birgisdottir and Christensen (Project M) developed an LCA model on bottom ash reutilization in road construction. Christensen and Bager (Project R) investigated reutilization of bottom ashes in road base constructions. Baun et al. (Project S) investigated reutilization of bottom ashes in relation to harbor construction.

It was found that bottom ashes combined with cement provided a product with sufficient strength to be used in road base layers; the leaching was found to be less than from bottom ashes in granular form (Christensen and Bager, Project R). Baun et al. (Project S) found that the leaching from bottom ashes reutilized in a marine environment as filler material was most important in the construction phase, and that the total release of contaminants is likely to be limited. With respect to reutilization in road construction, Crillesen and Hjelmar (Project E) found that understanding the flow patterns around the edges of the road were important for assessing leaching from roads.

The remaining projects have not yet reached conclusions.

Conclusions

The primary focus related to bottom ash reutilization have been given road construction or construction works in marine environments. Both areas need further development in the coming years in order to reach more detailed conclusions.

3.9 Design and operation

Objectives

It is generally agreed that potential for significant improvement of the bottom ash quality exists in optimizing incinerator operation. In this context, it is important to establish relationships between existing incinerator design and operation, and bottom ash quality.

Experiences

Nielsen and Clement (Project L) performed a survey of main parameters related to incinerator design and operation: furnace and grate type, residence time of waste, temperatures, and waste types incinerated. These informations were related to bottom ash composition and leaching. No conclusions have yet been reached.

The Danish plant owners Amagerforbrænding, Vestforbrænding and Elsam have in some cases experienced that better burnout of the waste resulted in less metal leaching; for example on furnaces equipped with rotary kilns. Likewise, it may have consequences for the bottom ash quality whether grate siftings are returned to the furnace or directly mixed with the bottom ashes. At some plants, boiler ashes are mixed with bottom ashes; this may also affect the quality. The redox conditions during incineration on the grate may also influence the leaching properties of the bottom ashes.

Overall, there can be no doubt that design and operation of the incinerator may profoundly influence the bottom ash quality.

Conclusions

Currently, the primary focus is to establish overall relationships between incinerator design and bottom ash quality. At this time, no detailed investigations have been completed concerning the importance of incinerator operation for the ash quality. This area will require substantial development in order to provide the knowledge necessary to optimize incinerator operation.

Chapter 4

Technical status and development needs

4.1 Technical status

The experiences gained in Danish projects within recent years can be summarized by the following conclusions.

Bottom ash quality in general

- The bottom ash composition significantly varies between different incinerators. These variations are likely caused by variations in waste input as well as the incinerator technology and mode of operation.

- The bottom ash leaching as determined by standard leaching tests significantly varies between incinerators. These variations may be caused by differences in bottom ash composition, but may also be significantly affected by incinerator technology and mode of operation.

- The bottom ash quality can vary significantly over time for a specific incinerator, both with respect to solid composition and leaching. To some extent, this may be explained by uncertainties related to ash characterization, but may also be caused by time wise variations in operation of a single furnace. This means that ash sampling, both routinely and in relation to specific projects, is very important.

- Bottom ashes are in most cases treated before reutilization, usually by curing and sorting. This improves the technical properties of the ashes and in many cases reduces the leaching. Usually, heavy metal leaching is decreased significantly; salt leaching may also decrease, but often the sulfate leaching increases.

- No bottom ashes can observe the criteria for reutilization according to category 1 in the statutory order. For most bottom ashes, it requires extensive treatment to sufficiently decrease leaching for reutilization under category 2, especially with respect to salts (namely sulfate), Cr, Cu, Ni, As and Pb.

Most bottom ashes can with some level of pretreatment be reutilized according to category 3; however, in some cases the limit values for Cu leaching may be very difficult to meet without extensive curing.

Sampling and characterization

- Bottom ashes are very inhomogeneous, even within a single batch. Taking representative samples from a specific ash quantity should be done only by considering the characteristics of the ashes, and only by using well documented sampling methods. The relative uncertainty on determination of the solid composition or the leaching properties of bottom ashes is typically in the order of 20–100 %.

- The criteria found in the Danish statutory order on ash reutilization do not account for the rather large uncertainties. For example, pH in the leaching test can significantly affect the test data. Also, the statutory order requires crushing of ash samples before leaching testing; crushing may not represent actual reutilization situations, in which cases the bottom ashes are not crushed.

Bottom ash leaching

- Bottom ash leaching, as determined by an L/S 2 batch test, typically amounts to less than one percent of the total heavy metal content, and for salts (Cl, Na and sulfate) in most cases about 30–100 % of the total content.

- The most important parameters with respect to heavy metal leaching is pH and dissolved organic matter (mostly important for Cu). The ash mineralogy, and thus the solubility controlling solid phases, is likely to control the leaching of salts and most heavy metals. Although investigations exist at an international level, no investigations have been done on Danish ashes. Knowledge on the mineralogy and the solubility controlling phases is important with respect to optimizing treatment processes including washing, and in relation to applying the results from leaching tests to actual reutilization scenarios.

- The distribution of critical components with respect to particle size has only in one case been documented in detail on Danish bottom ashes. Especially the heavy metals are expected to be concentrated in the small sized particles, but the results reported have not been conclusive in this respect. The element distribution is likely to affect the leaching, and may affect the possibilities of removing critical elements from the bottom ashes.

Improving bottom ash quality

- Bottom ash leaching determines the classification according to category 2 and 3 in the Danish statutory order. Improvement of bottom ash quality according to this classification therefore involves an improvement of the leaching properties of the bottom ashes.

- Curing for a few months allows hydration and carbonation of the bottom ashes as well as stabilization of the organic matter in the ashes. The mechanism for transforming the organic matter is not yet known to an extent that may be used for optimization of the curing process.

- Curing decreases pH and the leaching of most heavy metals, while sulfate leaching is often increased. The increase in sulfate leaching is likely caused by a change in solubility controlling mineral during curing: at high pH minerals with lower solubility controls leaching, while at lower pH gypsum controls the leaching resulting in higher sulfate concentrations.

- In some cases, curing decreased Na and Cl leaching. Excessive rain during the time of curing may wash out these salts from the ashes. However, also changes in grain size distribution in the bottom ash heap may explain changes in leaching if such variations are not accounted for during sampling.

- Curing significantly improves both the heavy metal leaching and the geotechnical properties of bottom ashes with respect to reutilization, but curing alone may not ensure that leaching is below the limit values for category 2. In most cases, extended curing for up to 12 month can ensure leaching below the limit values for category 3.

- During washing, considerable amounts of salts dissolve resulting in a decrease in Na and Cl leaching. Sulfate leaching is not significantly decreased by washing. This is most likely due to the fact that sulfate leaching is solubility controlled and therefore not significantly affected by removal during washing. In some cases, washing improves leaching of Pb, Cr and Cu, but Cu leaching is still above the limit values for category 2.

- Washing with addition of $NaHCO_3$ may give a better result for sulfate, but typically not to an extent that brings leaching below the limit values for category 2. The added Na may be removed by washing. In some cases also Cu, Cr and Pb leaching can be improved by washing with $NaHCO_3$, although this may be caused by pH decreases induced by the added carbonate. It should be noted that such decreases in pH are significantly less than pH changes during leaching. In full scale plants, technical problems have been related to $NaHCO_3$ dosing.

- Washing with addition of CO_2 may to a similar extent improve metal leaching; however, no significant effect can be associated to sulfate leaching.

- In general, it is difficult to ensure leaching below the limit values in category 2 by washing with a reasonable volume of water (about 2-5 m^3/ton). Some bottom ashes may, however, observe the limit values in category 2 with the current ash processing.

- Recovery of magnetic and non-magnetic metals (primarily Al, Cu, brass, and stainless steel) from bottom ashes appear technical possible and potentially profitable. The effect on metal leaching of removing metals from bottom ashes has not been investigated, but it seems unlikely that metal leaching is controlled by the content of metal objects in the ashes.

- Optimizing furnace operation most likely has a major potential for improving the bottom ash quality; for example, ash burnout and redox conditions on the grate are generally expected to affect bottom ash quality and leaching.

Bottom ash reutilization

- The geotechnical properties of bottom ashes ensure that bottom ashes provide a good alternative to virgin materials used in construction works. From a technical point of view, no major hindrance exists for bottom ash reutilization. Today, about half the Danish bottom ashes are reutilized according to category 3 in the statutory order while the other half are reutilized according to special permits or exemptions from the statutory order.

- A main barrier for reutilization is the fact that the site receiving the ashes is registered as contaminated according to the Danish legislation. As this registration occur regardless whether the bottom ashes are reutilized according to category 2 or 3, no incentive for upgrading the ashes exist.

- The most important restriction in reutilization options in category 3 compared with category 2 is the fact that bottom ashes in category 3 may not be used for construction of squares. As this is a relative important market possibility, and upgrading bottom ashes from category 3 to category 2 may be difficult, this is practically a barrier for reutilizing the ashes.

- According to the statutory order on residue reutilization, bottom ashes are not allowed to the be stored on site without cover for more than one month. Typical work procedures for example in road construction require that the base layer is established before adding the top layer (e.g. asphalt); in many cases, this may not be possible within the one month limit.

4.2 Needs for development

Based on the Danish projects, a considerably improved understanding on bottom ash leaching and the possibilities for upgrading bottom ash quality has been provided. However, it should be realized that a detailed description of the underlying mechanisms and processes has not been given, and that no single pretreatment process has been suggested to ensure reutilization according to category 2 in the statutory order. Generally, the most critical parameters are Cu and sulfate.

The following development needs have been identified with respect to upgrading bottom ash quality:

- For all bottom ash reutilization, whether in granular or monolithic form, curing will improve the ash quality. Thus, a more detailed understanding of the involved processes is needed. The parameters (e.g. temperature, water content, aeration) controlling the subsequent leaching properties should be investigated. On this basis, curing may be optimized and leaching minimized.

- Sulfate is a critical parameter, and a more detailed understanding of the solubility controlling phases in relation to curing and washing is important for optimizing these processes.

- Cu is a critical parameter, and a more detailed understanding of the mechanism for Cu leaching as well as attenuation in soils below reutilized bottom ashes is necessary for assessing Cu migration from areas with bottom ashes. Also, it should be investigated whether Cu may bind to particles and be transported as colloids.

- Relevant limit values for leaching from bottom ashes in monolithic form should be determined as is the case for granular materials. This is needed with respect to reutilization of bottom ashes in road construction when stabilized with cement, and in the case of larger construction works requiring special permits.

- Guidelines for approval of specific reutilization projects should be made available. Also, tools for performing environmental assessments as part of the overall approval procedure should be developed. Such tools should include estimations of potential leaching from reutilized bottom ashes of critical elements (natural attenuation, migration distance, concentrations, amounts).

- The potential for using a leaching test with a fixed pH when evaluating bottom ash samples relative to the limit values should be investigated. It is anticipated that a fixed pH will result in a more robust leaching test, and that variations within a bottom ash heap may be less pronounced. As a consequence, the overall uncertainty on the result may be decreased.

- Storage of bottom ashes is allowed without cover for up to one month; the potential leaching should be evaluated in case of storage for more than one month.

- The importance of crushing bottom ash particles to less than 4 mm in leaching tests should be evaluated with respect to actual reutilization scenarios; in real-life reutilization projects, bottom ashes are not crushed.

- Although a robust treatment option ensuring bottom ash reutilization has not been identified, it is suggested to define a best-available-technique, and test this in pilot scale on a range of bottom ashes in order to demonstrate the obtainable quality. The results can subsequently be evaluated relative to the current limit values, and be used in an integrated environmental assessment bases on life cycle principles.

- The long-term aspects of leaching from bottom ashes in category 1 and 2 should be investigated in more detail.
- The influence on bottom ash quality from waste characteristics and operational conditions in the furnace should be investigated in more detail.
- New reutilization options should be further developed in order to improve marketing possibilities.

4.3 Disposal scenarios

The future possibilities for disposal of bottom ashes in Denmark are to a great extent determined by the legislation. Based on the current legislation and the current state of knowledge, the most likely disposal scenarios are outlined in the following reflecting the Danish situation. For each scenario, specific needs for development are summarized (A–J).

Export

Bottom ashes are mainly exported for reutilization in other countries. Export for reutilization needs approval from the Danish EPA. No specific development needs have been identified for this scenario.

Status quo

Bottom ashes are cured in order to restrict leaching to below the limit values in category 3. Reutilization take place according to the possibilities in category 3, with special permission according to the possibilities in category 2, or according to the regulations in the Environmental Protection Act. This scenario will most likely result in needs for additional storage capacity. The main development needs are:

A Environmental assessment of likely disposal scenarios, including an evaluation of the importance of the bottom ash quality for the environmental consequences in a long-term perspective.

B Tools and guidelines for assisting environmental assessments of specific reutilization projects.

Best possible quality

The bottom ash quality is improved as much as possible using a broad range of approaches and pretreatment techniques while still considering the environmental costs associated with the processing. The bottom ashes are expected mainly to be reutilized according to category 3, or with special permission according to the possibilities in category 2, or according to the regulations in the Environmental Protection Act. The main development needs are:

A Environmental assessment of likely disposal scenarios, including an evaluation of the importance of the bottom ash quality for the environmental consequences in a long-term perspective.

B Tools and guidelines for assisting environmental assessments of specific reutilization projects.

C Further development of pretreatment technologies and demonstration of promising technologies in larger scale.

D Further investigation of the geochemical processes related to bottom ash pretreatment to increase the understanding of controlling mechanisms.

New reutilization options

New options for reutilization are developed in order to improve market possibilities. The bottom ashes are processed as needed by the individual reutilization options. The bottom ashes are expected mainly to be reutilized after special permits according to the Environmental Protection Act. The main development needs are:

A Environmental assessment of likely disposal scenarios, including an evaluation of the importance of the bottom ash quality for the environmental consequences in a long-term perspective.

B Tools and guidelines for assisting environmental assessments of specific reutilization projects.

C Further development of pretreatment technologies and demonstration of promising technologies in larger scale.

D Further investigation of the geochemical processes related to bottom ash pretreatment to increase the understanding of controlling mechanisms.

E Further development of new reutilization options (e.g. marine environments, cement stabilized base layers in roads), and determination of the necessary ash quality.

F Determination of leaching criteria associated with specific reutilization options (e.g. monolithic materials).

Revision of legislation

The current statutory order regulating bottom ash reutilization in Denmark is revised on specific issues in order to better reflect the possibilities for pretreatment and reutilization. Based on this, it is assumed that the bottom ashes can be reutilized entirely within the framework of a revised statutory order.

This scenario is primarily supplementing the "Status quo" and "Best possible quality" scenarios. The focus should be placed on one or more of the following items:

- *Revision of limit values related to salt leaching.* Salt leaching from bottom ashes used for construction of roads and parking areas is likely to be of minor importance in areas where deicing is performed regularly; deicing of roads have been shown to have dramatic effects on nearby groundwater resources (Carlson et al., 1998). Limit values should be related to realistic background concentrations with respect to the reutilization options in question.

- *Revision of limit values related to leaching.* Based on controlled ash pretreatment it appears possible to reach a level close to the leaching criteria in category 2. A revision of the limit values should reflect a reasonable compromise between what may be achieved and what is desired from a strictly environmental point of view.

- *Revision of limit values related to metal leaching.* The limit values set forth in the statutory order are based on groundwater modeling; however, this modeling do not account for natural attenuation of heavy metals in the subsurface. Thus, the migration velocity is greatly overestimated in the modeling, and the high concentrations in the initial leachate are significantly less pronounced in real life situations.

- *Revision of associated leaching test.* Variations in pH, and thus the sampling, has major influences on the leaching data produced by the currently prescribed leaching test (an L/S 2 batch test). By relating the limit values to a leaching test with fixed pH, for example pH 9, the characterization will most likely be more robust towards variations in test conditions.

- *Reutilization of category 3 bottom ashes in squares, parking areas, etc.* The long-term environmental consequences of using bottom ashes in category 3 for construction of for example parking areas are most likely small compared with bottom ashes in category 2.

- *Revision of demands on ash storage.* Storage of bottom ashes without cover may from a practical point of view be necessary in road construction works. The long-term environmental consequences of extending the allowed storage time are most likely small.

The primary development needs are:

A Environmental assessment of likely disposal scenarios, including an evaluation of the importance of the bottom ash quality for the environmental consequences in a long-term perspective.

C Further development of pretreatment technologies and demonstration of promising technologies in larger scale.

D Further investigation of the geochemical processes related to bottom ash pretreatment to increase the understanding of controlling mechanisms.

G Development of new leaching criteria based on a leaching test with fixed pH.

H Environmental assessment of the potential heavy metal migration in soil and groundwater including effects from sorption and complexing at relevant hydrological conditions and relevant reutilization scenarios.

I Environmental assessment of the consequences of ash storage without cover for longer periods than currently allowed, e.g. depending on the time a year and the reutilization scenario.

J Further investigation of bottom ash leaching in full scale, and determination of the source term from reutilized ashes, for example in the construction of roads and parking areas.

Chapter 5

Literature

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Appendix A: Workshop participants

The following organizations and persons participated in the workshop 20 May, 2003 at Environment & Resources DTU:

AFATEK A/S Jørgen Skaarup, Jens Boddum

Babcock & Wilcox Vølund Erhardt Mogensen

DHI - Institut for Vand og Miljø Ole Hjelmar, Jette Bjerre Hansen, Dorthe L. Baun, Christian Grøn

dk-TEKNIK Susanne Westborg

Elsam A/S Affald & Energi Frits Unold

Elsam A/S Bo Sander, Svend Aage Jensen, Hans Møller, Charles Nielsen

I/S Amagerforbrænding Uffe Juul Andersen, Henrik Birch, Niels Møller Pedersen

I/S Reno-Nord Henrik Skovhaug

I/S Vestforbrænding Henrik Ørnebjerg, Kim Crillesen, Kirsten Bojsen

Institut för Geoteknologi, Lund, Sweden Peter Flyhammar

Miljø & Ressourcer DTU Thomas H. Christensen, Thomas Astrup, Harpa Birgisdottir, Christian Riber

RAMBØLL Tore Hulgård

RGS 90 A/S Karsten Ludvigsen

Sekretariat for Aluminium & Miljø Jim Hansen

SGI, Malmö, Sweden David Bendz

SYSAV, Malmö, Sweden Raul Grönholm, Tommy Nyström

Sønderborg Kraftvarme I/S Jens Chr. Hansen

Tech-wise A/S Michael Johansen, Jesper Staal

Vejteknisk Institut, VD Knud A. Pihl

Aalborg Portland Dirch H. Bager

Århus Kommunale Værker Erik Damgaard, Hanne Rasmussen, Preben Stjernholm

Appendix B: Projects summaries

The following pages provides short summaries of the individual projects A–B. For detailed information about project design, results and conclusions, please refer to the appropriate contact person for the project in question.

A Clinical waste and health issues related to bottom ashes at I/S Amagerforbrænding

The project investigated the effects of mixing the grate siftings with the bottom ashes (as opposed to returning the grate siftings to the furnace) during periods of incinerating clinical waste. Also, the effect of the water temperature in the ash transportation system was investigated. Samples of grate siftings and bottom ashes were characterized with respect to bacteria and pathogens during periods with and without incineration of clinical waste. The risk of infection was evaluated based on experiments in which marked and infected syringes were mixed with the normal clinical waste. It was found that grate siftings may be mixed directly with bottom ashes without causing increased risk of infection from the bottom ashes. Contact: Erhardt Mogensen, Babcock & Wilcox Vølund, `em@volund.dk`.

B Bottom ash washing with and without addition of $NaHCO_3$

The project investigated whether the bottom ash quality could be improved by washing in the quench tank at I/S Amagerforbrænding, with and without the addition of $NaHCO_3$. Several experiments were performed with various configurations of water and $NaHCO_3$ additions. The subsequent leaching was characterized by leaching tests before and after carbonation of samples. Leaching of SO_4^{2-} appeared not to be affected by $NaHCO_3$ addition in the washing process; however, the Cr leaching was affected. Cu leaching was correlated to DOC concentrations. Contact: Erhardt Mogensen, Babcock & Wilcox Vølund, `em@volund.dk`.

C Uncertainties related to bottom ash sampling

The project evaluated and quantified uncertainties related to a number of different sampling methods as well as the subsequent sample handling and processing. Ash samples were taken and analysed for selected elements. It was found that bottom ashes were rather inhomogeneous, and that cured ashes might react further after sampling. An especially large uncertainty was associated with Cu. Contact: Niels Møller Pedersen, I/S Amagerforbrænding, nmp@amfor.dk.

D Development in leaching during storing and curing

The project monitored leaching from a standard bottom ash heap by manual sampling over about six month. It was found that the current sampling procedure provided results with an acceptable relative uncertainty of about 30 %. Based on sampling at different heights in the ash heap, it was concluded that salts and metals had been transported downwards during storing. Contact: Jørgen Skaarup, AFATEK A/S, mail@afatek.dk.

E Demonstration of bottom ash reutilization

The project investigated the actual migration of contaminants from bottom ashes placed under roads, parking spaces, etc. Several sites each of 100-200 m^2 were established using bottom ashes as base layers with either asphalt or gravel as cover. Leachate collection was done form a number of sections below each site in order to evaluate water flow around the edges of the sites. Preliminary results indicated that effects of flow and infiltration around the outer edges of the sites were significant. Contact: Kim Crillesen, I/S Vestforbrænding, kc@vestfor.dk.

F Ferrox stabilization of bottmo ashes

Stabilization of heavy metals in bottom ashes was evaluated using the Ferrox process. This involved ash washing, addition of $FeSO_4$, and oxidation of Fe-oxides in order to provide binding capacity for heavy metals. The process reduced the leaching of Cu, Cr, Pb, and Zn. Contact: Kasper Lundtorp, Babcock & Wilcox Vølund, kal@volund.dk.

G C-RES incineration ash database

The project involved establishing of a database with information of bottom ash composition, leaching, handling, etc. Test results from specific samples could be entered, and the user could then compare with similar data from older samples and/or data from other plants. The database may be accessed from www.c-res.dk. Contact: Ole Hjelmar, DHI–Institut for Vand og Miljø, oh@dhi.dk.

H Bottom ash stabilization using washing, separation and storing

The project aimed to find a method for treating the bottom ashes in order to reduce leaching to below the limit values for category 2. Special focus was placed on SO_4^{2-} and Cu leaching. A number of experiments were done in the lab to identify the main factors affecting leaching from the ashes, e.g. equilibration time and particle size distribution. Samples were further treated with the additives Na_2CO_3, $NaHCO_3$, and CO_2 during washing. It was found that Na and Cl leaching could be decreased sufficiently with simple washing without additives, although several washing steps were needed. Leaching of Cu, Cr, and Pb was improved using additives in the washing process; the leaching data were in all cases close to the limit values. Contact: Jens K. Boddum, AFATEK A/S, jkb@afatek.dk.

I Technical and economical evaluation of separation of metals from bottom ashes

Based on information for existing sorting facilities, the technical and economical aspects of establishing a central Danish facility separating both iron and non-iron metals from bottom ashes were evaluated. Separation of non-iron metals were assumed done using eddy-current techniques. It was found that the sorted non-iron metals amounted to about 0.4 % per weight of the bottom ashes. The net cost of operating such a sorting facility in Denmark was estimated to about 3.5 DKK per ton of treated ash. Contact: Jesper Staal, Tech-wise A/S, jst@elsam-eng.com.

J Bottom ash washing

The project evaluated methods for washing of bottom ashes prior to reutilization in building and construction works. Two washing techniques were investigated: washing in the quench tank at I/S KARA, and washing in a soil washing facility. Experiments with various volumes of water were performed. Washing in the quench tank did not significantly improve leaching. Better results were observed using the soil washing facility. In this case, Na and Cl leaching was below category 2 limit values. SO_4^{2-} leaching was decreased but still above the limit values. Contact: Jens K. Boddum, AFATEK A/S, jkb@afatek.dk.

K Sorting of grain sizes

The project investigated a combined washing and separation process with the intention of removing salts and soluble heavy metals as well as the fine particle fraction. Experiments were done using a mobile wet-sorting facility. In this facility, bottom ashes were washed and separated in five fractions according to grain sizes. The experiments showed good results with respect to salt leaching, including SO_4^{2-}, and made it possible to remove the fine fraction (>0.06 mm) as well as an organic fraction. Contact: Kim Crillesen, I/S Vestforbrænding, kc@vestfor.dk.

L Bottom ash qualities

The project aimed at relating plant design and overall operation to bottom ash quality, and included a survey of major parameters at 25 Danish incineration plants. At the time of writing, no conclusions have yet arrived as the project was not finalized. Contact: Joan Maj Nielsen, COWI A/S, jmn@cowi.dk.

M LCA on bottom ash reutilization in road construction

The project aimed to establish a life-cycle assessment model for utilization of bottom ashes in road construction. The model implemented the UMIP methodology, and developed a computer program that based on default values and user input could evaluate environmental impacts of road construction scenarios. The project includes evaluation of selected cases, but at the time of writing the project was not finished. Contact: Harpa Birgisdottir, Environment & Resources DTU, hab@er.dtu.dk.

N Modeling of leaching from bottom ashes

The project focused on developing a mathematical model describing leaching from bottom ashes, and further aimed at investigating the importance of a number of processes affecting leaching, e.g. diffusion, dispersion, surface reactions, etc. Based on modeling of batch and column leaching data, it was found that diffusion processes were rate limiting during the first 10-40 hours of water contact while surface reactions were most important later. At the time of writing, only modeling of Cl, K, Na, Ca, and SO_4^{2-} were done. Contact: David Bendz, Swedish Geotechnical Institute, david.bendz@swedgeo.se.

O Bottom ash treatment

The project investigated washing of bottom ashes using $NaSO_4$ as an additive, and evaluated the results with respect to the category 2 limit values. A range of ash samples from five different incinerators were investigated in lab experiments using varying amounts of additive. It was found that washing with $NaSO_4$ decreased leaching below the limit values for Cl, Na, SO_4^{2-}, As, Cd, Ni, Pb, and Zn; however, sample crushing before leaching testing made it difficult to meet the limit values. Cr and Cu leaching were generally above the limit values, although some cured samples were below. It was recommended to further investigate ash washing in pilot scale, for example using a soil washing facility. Contact: Bo Sander, Elsam A/S, bos@elsam.com.

P Bottom ash separation

The project evaluated the potential for recovery of aluminum from bottom ashes based on full scale experiments. The sorting facility used a so-called detection/ejection technique as opposed to eddy-current techniques. Aluminum pieces were separated from a conveyor-belt using air-jets. Magnetic metals were separated using a magnet. Recovered non-magnetic metal was found to about 0.2–0.5 %, and the recovery of magnetic metal was found to about 3.6–7 %. The results were comparable with similar experiences in France and The Netherlands. Contact: Jim Hansen, Sekretariat for Aluminium & Miljø, alu-info@inet.uni2.dk.

Q Leaching of Cu and organic matter from bottom ashes

The project investigated relations between leaching of Cu and DOC from ashes generated at two different types of furnaces at I/S Vestforbrænding. The project included sample curing, leaching testing, organic matter fractionation, and microbial degradation experiments. It was found that organic matter may be converted during curing, and that organic acids may evaporate while other organic compounds may be bound to the ash particles. During the time of curing, aeration and watering were found to be key factors with respect to the subsequent Cu leaching. Contact: Christian Grøn, DHI–Institut for Vand og Miljø, chg@dhi.dk.

R Leaching from cement stabilized bottom ashes

The leaching from monolithic samples of cement stabilized bottom ashes were investigated in batch experiments. The leaching was measured as fluxes released by diffusion over 64 days. It was found that mixtures with 3–5 % cement produced a product with sufficient strength, and that the leaching was lower than for granular bottom ashes. Although, no limit values currently exist for monolithic materials, the leaching was concluded to most likely be below anticipated future values. Contact: Thomas H. Christensen, Environment & Resources DTU, `thc@er.dtu.dk`.

S Marine reutilization of bottom ashes

The project investigated the environmental consequences of reutilizing bottom ashes as filler material in marine environments. The project involved a range of lab and pilot scale leaching tests simulating harbor construction. It was found that lab scale leaching tests were sufficient for evaluating full scale leaching. Tank leaching tests revealed that release during the construction phase was limited by diffusion, and that leaching of trace elements over a decade would be less than 10 mg/m^2. Contact: Dorte Lærke Baun, DHI–Institut for Vand og Miljø, `dlj@dhi.dk`.

T Bottom ash curing, and washing with CO_2

The purpose of the project was twofold: to monitor development in leaching properties during curing, and to wash bottom ashes in the quench tank using CO_2 as additive. It was found that pH, Zn and Cu leaching decreased during the time of curing. Pb leaching was not affected by curing. Cu leaching was improved after washing, but no significant effect was observed from the additive. Ash washing did not show conclusive results concerning Zn. Contact: Kim Crillesen, I/S Vestforbrænding, `kc@vestfor.dk`.