

## Disposal strategies for municipal solid waste incineration residues

Ole Hjelm<sup>a</sup>\*

*VKI, Water Quality Institute, Agern Allé 11, DK-2970 Hørsholm, Denmark*

Received 23 November 1994; accepted 26 July 1995

---

### Abstract

An overview is presented of the various types of municipal solid waste incinerator (MSWI) residues produced, their characteristics and their leaching properties. It is established that short- and long-term leaching and release of contaminants constitute the most important potential environmental problems related to disposal of MSWI residues. A set of basic principles of waste disposal or leachate management strategy which takes the specific properties of the various types of residues into account and which may lead to sustainable waste disposal solutions is presented and discussed. Application of these principles to MSWI residues indicates that an environmentally sustainable disposal solution for MSWI bottom ash and air pollution control (APC) residues in the long term should be based on a controlled contaminant release strategy, i.e. a strategy which allows the leachate to leak into the surroundings at a controlled and environmentally acceptable rate. Leachate collection and treatment is therefore only required when such a disposal strategy is not feasible or during an initial stage of disposal. Landfilling of bottom ash is less problematic than landfilling of APC residues in terms of practical implementation of the disposal strategy and management of the leachate. Monofilling and separate management and disposal of MSWI bottom ash and APC residues are generally recommended.

*Keywords:* Incinerator; Residues; Disposal; Landfilling; Strategy; Leachate management; Leachate properties; Sustainability

---

### 1. Introduction

Incineration and landfilling are integral components of waste management in many countries across the world. The relative importance of incineration as opposed to direct landfilling varies substantially from country to country. Incineration is often the preferred option in countries with limited availability or accessibility of space

---

\* Tel.: +45 4286 5211. Fax: +45 4286 7273.

for landfilling. Switzerland, Japan, France, Germany, Sweden and Denmark are examples of countries in which 50% or more of the unrecycled waste is being or will be incinerated [1]; some of these countries have even passed legislation which will prohibit future landfilling of combustible waste [2, 3]. Incineration is also important (and will continue to increase in importance) in the USA, but at present the waste incinerated here only constitutes approximately 16% of the total municipal solid waste stream [1, 4].

Incineration reduces the volume of the waste by approximately 90% and allows for recovery of much of the energy bound in the waste. But the incineration process is not a final waste treatment stage. Combustion and air pollution control (APC) residues are produced and must subsequently be utilized or landfilled. In principle, at least in Europe, utilization of residues is generally preferred over landfilling, provided this does not give rise to unacceptable environmental impacts or health hazards. In practice, existing regulations, lack of economic incentives, liability issues, residue separation practices and uncertainty concerning the functional properties of the residues as well as uncertainties concerning the evaluation of the extent and acceptability of the environmental impacts and health hazards of municipal solid waste incinerator (MSWI) residue utilization often serve as obstacles to residue utilization. Landfilling or storage are therefore the dominating or only residue management options presently available in several countries. This is, e.g., the case in North America where most of the MSWI residues currently produced are landfilled, while in some European countries (e.g. Denmark, France, Germany and The Netherlands) significant quantities (40–60%) of the bottom ash from the MSWIs are actually being utilized for road construction and similar purposes [1]. Virtually all APC residues produced are landfilled or placed in underground storage facilities.

Due to the potential leaching of contaminants, landfilling of MSWI residues may have long-term consequences for the environment. The disposal solutions chosen for these residues should therefore be sustainable in terms of environmental impact and energy consumption.

This may be achieved only through careful consideration of the disposal strategies involved. The most important aspect of any disposal strategy is the short- and long-term management and fate of the leachate, and disposal strategies for MSWI residues (or any other waste) may therefore be defined chiefly in terms of leachate management.

The current disposal and leachate management practices for MSWI residues are rarely based on sustainability criteria and long-term strategies; instead, traditional sanitary landfilling techniques have generally been applied to the MSWI residues without any significant adjustments. The properties of MSWI residues are very different from those of uncombusted MSW, and while sanitary landfilling may be entirely appropriate for MSW, its application to MSWI residues may lead to disposal solutions which are less than optimal in terms of resource conservation and environmental safety, particularly in the long term. The purpose of this article is to present and discuss strategies or elements of strategies for disposal of MSWI residues which take the specific properties of these residues into account and which aim at a high degree of sustainability. The discussion of strategies is based primarily on

environmental/technical considerations and does not account for political, regulatory and economical aspects.

## 2. Characteristics of MSWI residues

The various types of residues produced by modern MSW mass burn incinerators are bottom ash, grate siftings, boiler ash, economizer ash, fly ash and acid gas scrubbing residues. The grate siftings and the boiler ash are often directly combined with the bottom ash, and economizer ash is nearly always combined with the fly ash which may be collected separately or as part of the acid gas scrubbing residues. In this article the term 'fly ash' is used exclusively for the fine particulates which are carried over from the combustor with the flue gases and subsequently captured in electrostatic precipitators or fabric filters; it does not (as it commonly does in North American terminology) include acid gas scrubbing residues. The bottom (or grate) ash which is the main waste stream from the incineration process appears after quenching/cooling with water as a coarse, extremely inhomogeneous granulate, usually containing larger, fused lumps of slag and pieces of scrap metal. The grate siftings may also be relatively coarse whereas the other residues are much finer powders or (from the wet scrubbing process) a wastewater treatment sludge.

The amount of each residue produced at an incinerator depends on several factors which may be summarized as feed waste composition, incinerator technology and operation, and air pollution control system technology and operation. Some typical amounts of MSWI residues produced are presented in Table 1.

Only the major solid waste streams from incineration, i.e. bottom ash, fly ash and acid gas scrubbing residues will be discussed. As mentioned above, the bottom ash stream often includes the grate siftings and the boiler ash, and the fly ash may include economizer ash. In the USA, the predominant MSWI residue stream is

Table 1  
Typical amounts of residues produced per metric ton of waste incinerated [5–7]

Type of residue	Typical amounts produced (kg/ton of feed waste)
Bottom ash	250–420
Grate siftings <sup>a</sup>	5
Boiler ash	2–12
Economizer ash	No data (small)
Fly ash	10–30
Acid gas scrubbing residues:	
– Dry process <sup>b</sup>	20–50
– Semidry process <sup>b</sup>	15–40
– Wet process <sup>c</sup>	1–3

<sup>a</sup> Only data from one incinerator.

<sup>b</sup> Including 10–30 kg fly ash.

<sup>c</sup> Dry weight of sludge from wastewater treatment; the process also produces 0.3–0.5 m<sup>3</sup> of treated wastewater containing 8–15 kg of calcium and sodium chloride. Fly ash is precollected separately.

*combined ash*, i.e. a mixture of bottom ash and APC residues (including fly ash) from dry/semidry scrubbing systems, whereas the bottom ash and fly ash and/or scrubber residue streams in most European countries are collected separately. Separate collection of the residue streams improves the utilization potential of the bottom ash (which constitutes 85–90% by weight of the residue stream) and limits the amount of more contaminated material (fly ash/scrubber residues) which must be managed more restrictively.

Table 2 shows ranges of composition of MSWI bottom ash (excluding the scrap metal portion and the size fraction larger than 45 mm which typically constitutes 10–20% of the total weight), fly ash, acid gas scrubbing residues from the dry and semidry processes which consist of mixtures of fly ash, reaction products (predominantly calcium chloride) and excess lime, and a mixture of precollected fly ash and wastewater treatment sludge from the wet scrubbing process.

From Table 2 it is seen that the major elements (those present in concentrations exceeding 10 g/kg) are nearly the same for all the residues shown: Si, Al, Fe, Ca, Mg, Na, K, S (except for bottom ash) and Cl (except for bottom ash), Zn (except for bottom ash) and Pb (only for fly ash). Many of the elements are present as oxides and O is therefore also a major element for all the residues. The concentration of the various trace elements varies between the different types of residues; some (e.g. Ba and Cr) are present at the same concentration level in all the residues, some (notably Cu) are usually enriched in the bottom ash, whereas several trace elements, particularly the more volatile elements (e.g. Cd, Hg, As, Pb and Zn) are enriched in the fly ash and acid gas scrubbing residues.

The various MSWI residues differ substantially from each other in terms of water solubility. Only a small fraction, often less than 1%, of the total mass of the bottom ash is soluble in water, whereas 20–25% of the total mass of the fly ash and 30–40% of the total mass of the dry/semidry acid gas scrubbing residues consists of salts which are readily soluble in water. The water solubility of an acid gas scrubbing residue from a wet scrubbing system (a mixture of sludge and fly ash) has been determined at 14 wt% [12]. The water solubility of the residues and the potential leaching and release of components which may adversely affect the environment are obviously important properties in relation to disposal/landfilling of the residues and management of the leachate.

### **3. Leachate from MSWI residues**

#### *3.1. Overview of leachability*

From a technical perspective, the development of strategies for disposal of MSWI residues and management of the leachate should be based on extensive knowledge of both the short- and long-term leaching behaviour of the particular types of MSWI residues in question. In this context, 'short term' may cover a time period of 25–50 years and 'long term' consequently represents the following several hundred to thousands of years.

Table 2  
 Ranges of composition of MSWI residues. Several of the elements are present as oxides and O is therefore also a major component

Parameter	Unit	Bottom ash Sources: [8-10]	Fly ash Sources: [9-11]	Acid gas scrubbing residues from the dry/semidry process (including fly ash) Sources: [12-14]	Acid gas scrubbing residues from the wet process (sludge mixed with fly ash) Sources: [12-14]
Si	g/kg	210-290	95-190	57-98	120
Al	g/kg	47-72	49-78	17-46	71-81
Fe	g/kg	27-150	18-35	3.6-18	15-18
Ca	g/kg	65-97	74-130	170-290	93-110
Mg	g/kg	7.7-19	11-19	7.1-12	18-23
K	g/kg	9.2-22	23-47	27-40	35-58
Na	g/kg	22-41	22-57	12-19	28-33
Ti	g/kg	3.2-7.2	7.5-12	1.5-5.1	5.3-8.4
S	g/kg	1.3-8	11-32	8-18	11-26
Cl	g/kg	1.2-3.2	45-101	92-220	48-71
P	g/kg	2.9-13	4.8-9.6	1.7-4.6	6.0-7.4
Mn	g/kg	<0.7-1.7	0.8-1.7	0.3-0.7	1.4-2.4
Ag	mg/kg	4.1-14	31-95	14-60	53
As	mg/kg	19-80	49-320	40-260	130-190
Ba	mg/kg	900-2700	920-1800	310-1400	330-1900
Be	mg/kg	nd	nd	0.5-0.9	1.5-1.9
Cd	mg/kg	1.4-40	250-450	140-300	220-270
Co	mg/kg	<10-40	29-69	4-15	14-22
Cr	mg/kg	230-600	140-530	150-570	390-660
Cu	mg/kg	900-4800	860-1400	450-1100	1000-1400
Hg	mg/kg	<0.01-3	0.8-7	9.3-44	38-390
Mo	mg/kg	2.5-40	15-49	9.3-20	20-38
Ni	mg/kg	60-190	92-240	20-63	67-110
Pb	mg/kg	1300-5400	7400-19,000	4000-6500	5900-8300
Se	mg/kg	0.6-8	6.1-31	8.2-16	12
Sn	mg/kg	<100-1300	1400-1900	620-780	1000

Table 2  
Continued

Parameter	Unit	Bottom ash Sources: [8-10]	Fly ash Sources: [9-11]	Acid gas scrubbing residues from the dry/semidry process (including fly ash) Sources: [12-14]	Acid gas scrubbing residues from the wet process (sludge mixed with fly ash) Sources: [12-14]
Sr	mg/kg	170-350	<80-250	400-500	200
V	mg/kg	36-90	32-150	26-62	62
W	mg/kg	<20-50	nd	nd	nd
Zn	mg/kg	1800-6200	19 000-41 000	12 000-19 000	20 000-23 000
PAH [15-18]	µg/kg	0.23-2200	30-110	18-5600	nd
CB [15-18]	µg/kg	6.7-45	50-890	220	nd
PCB [15-18]	µg/kg	<40	<40	<40	nd
CP [15-18]	µg/kg	16-34	120-1800	860	nd
PCDD [12,13,10,15,17,18]	µg/kg	0.2-10	115-140	0.7-1000	260
PCDF [12,13,10,15,17,18]	µg/kg	0.44-4.5	48-69	1.4-370	120
TCDD-equiv <sup>a</sup>	µg/kg	0.02-0.22	1.5-2.5	0.8-2	2.8
TOC	g/kg	4.8-13	4.9-17	6-9	7
LOI	g/kg	5.9-50	11-45	28-49	110

<sup>a</sup>TCDD-toxicity equivalents determined according to Eadon's method [10,12,13].

nd: No data available.

PAH: Polycyclic aromatic hydrocarbons.

CB: Chlorobenzenes.

CP: Chlorophenols.

PCDD: Polychlorinated dibenzo-*p*-dioxins.

PCDF: Polychlorinated dibenzofurans.

TOC: Total organic carbon.

LOI: Loss on ignition (550 °C).

A reasonable amount of information is available on the short-term behaviour of most MSWI residues, and the evaluation of the short-term behaviour may to a large extent be based on the results of laboratory and pilot-scale leaching experiments and field observations.

The long-term behaviour of MSWI residues is much less understood. Due to the lack of direct observations, the evaluation of the long-term behaviour is more complicated and requires a synthesis of information obtained from laboratory testing of fundamental leaching behaviour, leaching tests simulating long-term disposal conditions, field measurements and hydrogeochemical modelling of mineral changes and speciation. The results of ongoing and future research in this field may be expected to reduce the substantial degree of uncertainty with which predictions of the long-term behaviour of MSWI residues are currently made.

Table 3 presents an overview of the maximum levels of concentrations of inorganic salts, trace elements and non-volatile organic carbon (NVOC) observed in initial leachates from the major types of MSWI residues: Bottom ash (usually including grate siftings and boiler ash), fly ash and mixtures of fly ash and acid gas scrubbing residues from the semidry process and dry lime injection process, and a mixture of fly ash and sludge from treatment of the wastewater from the wet scrubbing process with lime and trimercaptotriazine, TMT [19]. The maximum concentrations shown in the table represent data from a number of laboratory leaching tests (mostly column leaching tests) and a few field investigations [10–13, 20, 21].

The maximum concentrations occur in the initial leachate for most parameters (note, however, the sulphate curve in Fig. 1), and most of the concentrations in Table 1 have been observed in samples of leachate collected at or below  $L/S = 0.5$  l/kg.  $L/S$  = liquid/solid or leachate/waste ratio, e.g. expressed as cubic meters of leachate produced per tonne of waste or residue deposited. For a particular disposal site  $S$  will be constant and  $L$  will increase as the leachate is formed; an  $L/S$  scale may therefore be transformed to a time scale if the rate of percolation

Table 3  
Maximum concentration levels of contaminants in leachates from various MSWI residues

Typical maximum levels of concentration in leachate	MSWI bottom ash	MSWI fly ash and residues from dry and semidry APC processes	Mixture of MSWI fly ash and sludge from wet scrubbing process
>100 g/l		Cl <sup>-</sup> , Ca	
10–100 g/l		Na, K, Pb	Cl <sup>-</sup> , Na, K
1–10 g/l	SO <sub>4</sub> <sup>2-</sup> , Cl <sup>-</sup> , Na, K, Ca	Zn	SO <sub>4</sub> <sup>2-</sup> , Ca
100–1000 mg/l	NVOC, NH <sub>4</sub> -N	NVOC, SO <sub>4</sub> <sup>2-</sup>	
10–100 mg/l			
1–10 mg/l	Cu, Mo, Pb	Cu, Cd, Cr, Mo	NVOC, Mo
100–1000 µg/l	Mn, Zn	As	
10–100 µg/l	As, Cd, Ni, Se		As, Cr, Zn
1–10 µg/l	Cr, Hg, Sn		Pb
<1 µg/l		Hg	Cd, Cu, Hg

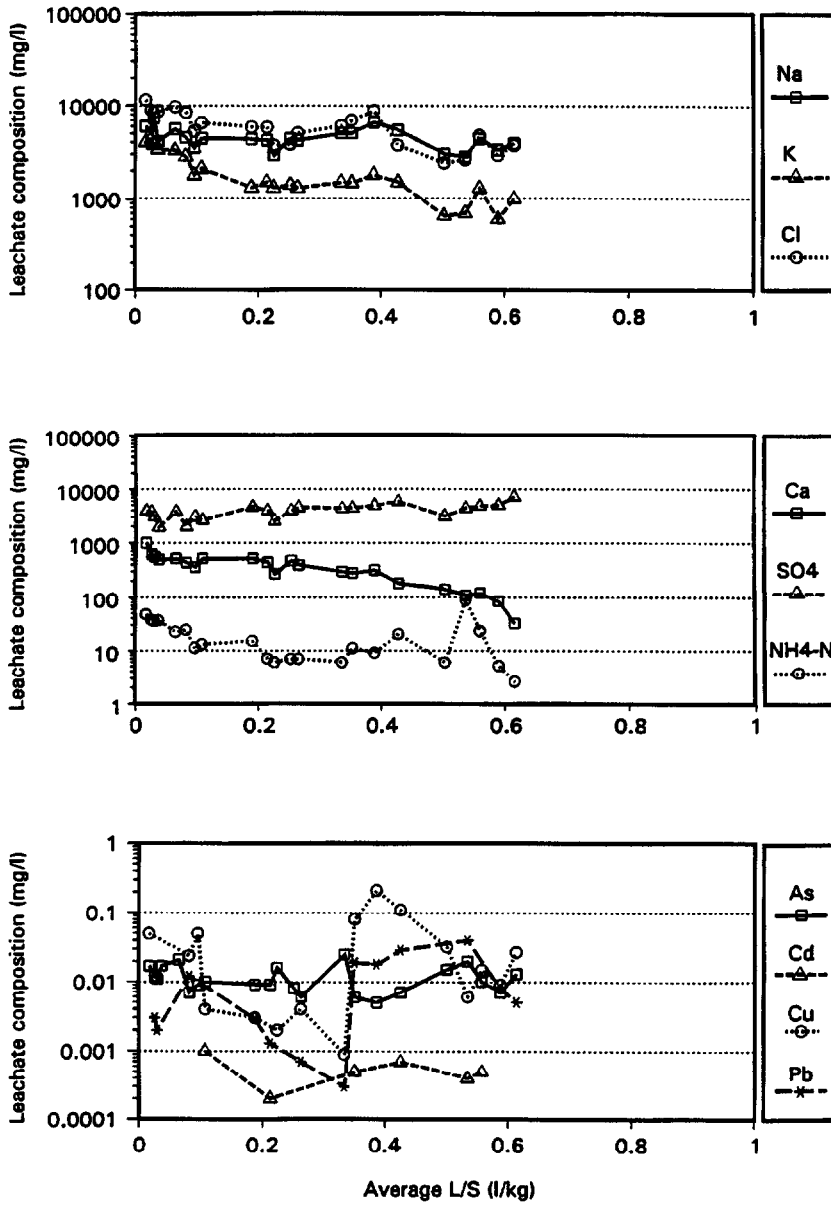


Fig. 1. MSWI bottom and fly ash monofill leachate composition vs. L/S measured over a period of 20 years at Vestskoven, Denmark.



or flow through the site is known. It is often practical to express field data and experimentally determined data on leachate quality as a function of L/S for, each particular system in question. Such data may subsequently be used (with caution!) in conjunction with additional information (e.g. on pH and redox conditions) to predict leachate quality as a function of time at a disposal site which contains waste/residues with similar properties and for which the rate of percolation of water is known. At low L/S values, the leaching of several contaminants, particularly trace elements, is solubility controlled and strongly influenced by the pH of the leachate (which in turn is governed by the major constituents of the MSWI residues and local conditions).

As often documented, e.g. by [22], MSWI residues show systematic leaching patterns, and the leaching behaviour of several contaminants is controlled by such factors as pH, redox potential, ionic strength, complexing inorganic ions and organics, the presence of various minerals, etc. Once the relationship between the controlled contaminants and the controlling factors has been established, it becomes important to be able to predict how these controlling factors may develop within a MSWI residue disposal site. The estimation of contaminant release from disposal of MSWI residues is discussed in detail by Kosson et al. [23].

### 3.2. *Bottom ash leachate*

Table 4 shows the development over a period of 20 years of the quality of leachate from a Danish MSWI ash monofill, Vestshoven, containing approximately 10 000 tonnes of bottom ash with an estimated content of 15% fly ash. The data in the table is based on annual analyses of the leachate which is contained by a PVC bottom liner, conducted to a central pumping sump and pumped out at regular intervals. In 1992, a total of 6150 m<sup>3</sup> of leachate had been removed from the MSWI ash monofill which has been described extensively elsewhere [9, 20, 24]. The concentration of some of the major components and trace elements in the leachate is shown as a function of L/S in Fig. 1.

For bottom ash, the first leachate has a relatively high content of inorganic salts (chloride, sulphate, sodium, potassium, calcium). The contents of dissolved organic matter (measured as NVOC) and ammonia are both associated with the residual uncombusted organic material and may vary considerably. The pH is usually slightly to strongly alkaline (depending on the degree of carbonation). The redox potential is low (reducing) due to microbiological degradation of the residual organic material. The concentrations of trace elements in the leachate are low due to the reducing environment (most of them form relatively insoluble sulfides) and the favourable pH regime. The content of uncombusted organic material in MSWI bottom ash may be one of the key factors in controlling the hydrogeochemical conditions and hence the behaviour of trace elements within a bottom ash landfill. It may be a delicate balance: Enough organic material should be present to support a certain microbiological activity but the content of the organic material and the organic degradation products should, on the other hand, not be high enough to dominate the composition of the leachate. In order not to mobilize trace elements, the amount

Table 4

Overview of a time series of leachate quality measurements from a 20 years old Danish MSWI bottom and fly ash monofill, Vestsikoven. The content of fly ash is estimated at 15%

Parameter	Unit	Variation 1973–92 (22 observations)	Average values	
			1973/74	1991/92
pH	—	8.7–10.5	8.8–10.1	8.9–10.2
Alkalinity	meqv/l	1.4–9.3	2.5	7.4
Redox potential, $E_h$	mV	–10–290	–66	—
Conductivity	mS/m	1400–3900	3100	1900
BOD5 (from 1981)	mg/l	< 2–26	—	2
Sulphate	mg/l	2000–7200	3100	6100
Chloride	mg/l	2400–11 400	9300	3300
Ammonia-N	mg/l	2.6–87	39	3.9
Na	mg/l	2800–7300	5600	3600
K	mg/l	600–4300	3900	800
Ca	mg/l	32–1000	670	58
As	mg/l	0.005–0.025	0.014	0.010
Cd	mg/l	< 0.0001–0.001	< 0.003	< 0.0002
Cr	mg/l	< 0.001–0.08	0.03	< 0.002
Cu	mg/l	< 0.0005–0.21	0.013	0.018
Fe	mg/l	< 0.01–0.76	0.21	0.055
Hg	mg/l	< 0.00005–0.003	0.00008	0.0004
Pb	mg/l	< 0.0005–0.04	0.0013	0.007
Zn	mg/l	< 0.01–0.59	0.05	0.09
Ionic strength	gmol/l	0.18–0.48	0.41	0.23
Accumulated L/S	l/kg	0.017–0.615	0.027	0.602

of acidic degradation products must not be significant in comparison to the acid neutralization capacity of the bottom ash. Dissolved organic material per se is an undesired contaminant, and it has further been shown to be associated with increased mobility of Cu in MSWI bottom ash [25]. From Table 4 and Fig. 1 it can be seen that there is a tendency for the concentrations of most salts in the leachate to decrease as the leaching progresses (note, however, that sulphate concentrations are actually increasing due to the decrease in calcium concentrations). Reducing conditions are maintained and the concentrations of trace elements remain low during the 20 years of observation at this particular site. The low short-term concentration level of most trace elements have been confirmed by observations at other MSWI ash landfills [24].

### 3.3. Fly ash and acid gas scrubbing residue leachate

An impression of the leaching properties of fly ash and acid gas scrubbing residues may be obtained from the results of laboratory studies of 8 products (3 fly ashes, 2 dry, 2 semidry and one wet process product, [10, 12, 13]). Field observations and large-scale lysimeter leaching tests have subsequently confirmed these findings [26].

The studies indicated that the acid gas scrubbing residues from the semidry and dry processes contain 20–35% (w/w) readily soluble material. Most of the soluble

material which primarily consists of chlorides and hydroxides of calcium, sodium and potassium appears in the first few fractions of leachate ( $L/S = 0$  to 2 l/kg). The most leachable metals/trace elements are lead (2.3–65% (w/w) of the total content) and molybdenum (9–19% (w/w) of the total content). All other trace elements were less than 4% (w/w) leachable under these circumstances, and most of them far less than 1% (w/w) leachable. The high leachability of lead is caused primarily by chloride complexation but the amphoteric behaviour of lead also plays an important role at pH values above 10 to 11. No releases of mercury, nickel and tin were observable. Concentrations of soluble matter are very high in the first leachate fractions from the dry and semidry products but level off to moderate and low values in later fractions (see Table 5). The leachability of the fly ash resembles that of the dry and semidry acid gas scrubbing residues, although the leaching of Ca and the alkalinity of the leachate is much smaller for the fly ash. The pH of the fly ash leachate is generally lower than that of the dry/semidry residue leachate which under certain circumstances may cause some differences in leachability of, e.g., Cd.

The residue from the wet scrubbing process was shown to have a content of readily soluble material which was considerably smaller than that of the dry and semidry residues. The major ions in the initial leachate fractions are chloride, sodium, potassium, and to a lesser extent calcium. Sulphate is present in appreciably higher concentrations than in the leachates from the dry/semidry products. With molybdenum as the only exception, the concentrations of trace elements/heavy metals are low in all leachate fractions, probably due to the presence of the organic sulfide TMT. The long-term stability and effectiveness of TMT is not known. The highest concentration of lead measured in the leachate from the residue from the wet scrubbing process was 1000 times lower than the lowest concentration measured in the initial leachates from the dry and semidry residues.

### 3.4. Combined ash leachate

As mentioned previously, bottom ash and APC residues are generally managed and landfilled separately in Europe, and as a mixture (combined ash) in the USA. Some of the short-term effects on the leachate quality of adding the highly soluble residues from the semidry APC process to the bottom ash prior to disposal are seen in Table 6 which presents leachate quality data from a combined ash monofill, the Woodburn Landfill, in Oregon, USA [27]. A comparison of Table 6 with Table 4 shows that the concentrations of soluble inorganic salts, particularly chloride and calcium from the acid gas cleaning residues, are substantially higher in the combined ash leachate than in the bottom ash (and fly ash) leachate. The higher concentrations of Cd (up to 0.6 mg/l as compared to a maximum value of 0.025 mg/l at Vestskoven) which have been observed at the Woodburn Landfill are consistent with the lower pH and the high (complexing) chloride concentrations. The lower pH at the Woodburn Landfill may be caused by organic acids produced by biodegradation of residual unburnt material in the bottom ash which may possibly be higher at Woodburn than at Vestskoven. This would also be consistent with the relatively high levels of iron observed in the leachate from the Woodburn Landfill.

Table 5

Results of column and batch leaching tests on fly ash (ranges for 3 ashes) and residues from the dry and semidry processes (ranges for 4 products) and wet scrubbing product (single determination). Composition of the first ( $L/S = 0.0\text{--}0.2$  l/kg) and the last ( $L/S = 5.0\text{--}25$  l/kg) leachate fractions

Parameter	Unit	Fly ash	Residues from dry and semidry processes	Residues from wet scrubbing process
<i>First leachate fraction (L/S = 0.0–0.2 l/kg)</i>				
pH	—	7.3–9.4	9.8–10.2	9.0
TDS	mg/l	400 000–410 000	430 000–520 000	116 000
Alkalinity	meqv/l	1.2–2.9	87–540	0.96
Chloride	mg/l	230 000–240 000	190 000–310 000	65 000
Sulphate	mg/l	240–590	150–430	2100
Ca	mg/l	16 000–35 000	110 000–160 000	5800
Na	mg/l	39 000–87 000	7500–37 000	23 000
K	mg/l	51 000–53 000	19 000–66 000	23 000
Cd	mg/l	0.20–160	0.099–1.9	0.0006
Cr <sup>a</sup>	mg/l	0.02–0.004	0.48–2.3	< 0.003
Cu	mg/l	0.01–1.4	0.17–37	0.0009
Hg	mg/l	< 0.0005–0.001	< 0.003	< 0.0005
Mo <sup>a</sup>	mg/l	4.0–5.0	0.31–0.61	7.9
Pb	mg/l	0.36–1900	2.2–11 000	0.0019
Zn	mg/l	0.5–3200	0.02–730	0.02
NVOC	mg/l	7–39	24–640	8
<i>Last leachate fraction (L/S = 5.0–25 l/kg)</i>				
pH	—	10.7–11.2	12.1–12.5	10.6
TDS	mg/l	380–2400	770–1900	1600
Alkalinity	meqv/l	0.9–2.2	13–42	2.0
Chloride	mg/l	5–9	20–36	2.8
Sulphate	mg/l	190–1500	2.5–40	1100
Ca	mg/l	110–650	290–840	460
Na	mg/l	2–8	8–24	15
K	mg/l	4.1–15	10–41	19
Cd	mg/l	0.00003–0.00008	< 0.00002–0.00006	< 0.00002
Cr	mg/l	0.0007–0.005	< 0.004–0.004	0.023
Cu	mg/l	0.0002–0.001	0.002–0.007	< 0.0005
Hg	mg/l	< 0.0005	na	na
Mo	mg/l	0.08–0.2	0.017–0.075	0.027
Pb	mg/l	0.4–0.9	4.3–8.6	< 0.0001
Zn	mg/l	< 0.05	0.48–1.5	< 0.02
NVOC	mg/L	0.1–1	1.9–4.0	2.8

<sup>a</sup> Combined fraction  $L/S = 0.0\text{--}1.0$  l/kg analysed.

na: Not analysed.

#### 4. Disposal of waste: Objectives and basic principles

##### 4.1. Objectives

The primary objective of disposal of waste is to remove from general circulation materials/products that are no longer useful in any respect, and preferably to do this

Table 6

Results of analyses of leachate from a combined ash monofill, the Woodburn Landfill, in Oregon, USA over a period of 5 years. From [27]

Parameter	Unit	Variation 1988–1993
pH	—	5.7–7.5
TDS	mg/l	14 000–73 000
TOC	mg/l	4–110
Sulphate	mg/l	80–1500
Chloride	mg/l	7700–50 000
Ammonia N	mg/l	< DL–35
Na	mg/l	3000–9300
K	mg/l	520–6900
Ca	mg/l	1300–16 000
As	mg/l	< DL–0.4
Cd	mg/l	< DL–0.6
Cr	mg/l	< DL–0.03
Cu	mg/l	< DL–0.6
Fe	mg/l	< DL–32
Hg	mg/l	< DL
Pb	mg/l	< DL–0.14
Zn	mg/l	< DL–1.6

TDS: Total dissolved solids.

TOC: Total organic carbon.

DL: Detection limit.

in a manner which eventually returns the basic constituents of the waste to the ecological cycle.

A second and equally important objective of waste disposal is to ensure that the waste does not cause any unacceptable short- or long-term impacts on the environment or on human health. Disposal of MSWI residues is usually accomplished through landfilling. This should preferably be done in a sustainable manner, i.e. without excessive and/or prolonged maintenance or operation requirements, and without a prolonged need for aftercare. In effect, this implies that each human generation must take care of its own waste.

#### 4.2. Basic principles and elements of strategy

The following represents an attempt at developing a set of basic principles which, when observed by a disposal strategy for MSWI residues (or other types of waste), are likely to ensure that the above-mentioned objectives are met. These basic principles, which are discussed in more detail below, are:

- Landfills should be designed to minimize the required lifetime of active environmental protection systems (i.e. systems requiring maintenance or operation).
- Any disposal strategy should reflect the inherent properties of the waste.
- Landfill design, operation and siting must be adapted to the admitted waste in such a manner that long-term emissions of leachate (and gas) become or remain environmentally acceptable.

- Any strategy for landfilling must include consideration of the ultimate fate of the leachate and the residues remaining in the disposal site as well as derived effects of disposal and leachate management.

The major environmental concern in relation to the short- and long-term impacts of MSWI residue disposal is the risk of leaching and subsequent release of potentially harmful substances, particularly inorganic salts and trace elements, into the environment. In the short term, especially during the landfilling period, fugitive dust may also be of some concern. Fugitive dust problems, however, may be avoided relatively easily by applying simple control measures and will not be addressed further in this context.

#### *4.2.1. Landfills should be designed to minimize the required lifetime of active environmental protection systems*

Both active environmental protection systems (i.e. systems for collection/removal, transport and treatment of leachate which require maintenance or operation) and passive environmental protection systems (i.e. systems such as geologically stable low permeable top covers and barriers and surface drains that do not require operation or maintenance) must be designed and constructed to ensure that they perform as intended for their intended lifetime. For a strategy based on restricted percolation of infiltrated precipitation through mineral wastes such as most well combusted MSWI residues, this could in some cases require system lifetimes of several hundred years or more.

It is generally assumed that traditionally landfilled raw MSW as well as several other wastes will become harmless in the course of time, and that a landfill therefore may be safely abandoned and forgotten after a period of e.g. 30 or 50 years. However, neither the criteria determining whether or not it will be safe to abandon a site and leave it without active environmental protection systems nor the length of time needed to reach this point are generally well defined or known. Both depend strongly on the exact nature of the waste and on local conditions, both within the landfill and in the surrounding environment.

Based on a number of assumptions, Belevi and Baccini [28] have calculated that it may take 500–1700 yr before the content of organic C in the leachate from a traditional 'sanitary' landfill has been reduced to a level of 20 mg/l. They have also calculated that it may take 55–80 yr for the concentration of  $\text{NH}_3 + \text{NH}_4^+$  to decrease to 5 mg/l, 100–700 yr for P to decrease to 0.4 mg/l and 100–150 yr for  $\text{Cl}^-$  to decrease to 100 mg/l. In relation to groundwater and surface water protection, it is often the concentrations of ammonia which remain high over a considerable period of time that are of major concern.

In a recent study [29], a very simplified estimation has indicated that for a 12 m high landfill and an assumed rate of infiltration/production of leachate of 200 mm/yr, average periods of approximately 300 yr and 100 yr might be required for landfilled raw MSW and some inorganic waste types (e.g. MSWI bottom ash), respectively, to reach 'final storage quality', i.e. a condition which allows the site to be safely abandoned without active environmental protection systems. An increased rate of

infiltration may shorten these time periods, and a decreased rate of infiltration may lengthen them.

Both from a legal and a practical perspective a target maximum aftercare period of 30–50 yr, after which the environmental safety of the landfill should no longer rely on active environmental protection systems, seems appropriate. As seen above, however, for several types of waste this target aftercare period may not be realistic without changes in current landfill operation and design.

#### *4.2.2. Any disposal strategy should reflect the inherent properties of the waste*

There may be fundamental differences between leachates produced by different types of waste; leachate from relatively stable mineral waste (e.g. well-combusted MSWI bottom ash) behaves very differently from that produced by more reactive, biodegradable types of waste (e.g. raw MSW such as domestic waste, garden refuse). These differences should be reflected in the disposal and leachate management strategy chosen for each type of waste. Types of waste that are incompatible in terms of disposal strategy should be directed to different categories of landfills.

When deposited in a sanitary landfill, raw MSW dominated by organic, biodegradable waste components is normally decomposed and eventually mineralized to ammonia, hydrogen, carbon dioxide and methane. During the first several years after landfilling, the leachate generated will contain relatively high concentrations of organic compounds, and it does therefore make sense, both from an environmental and a technical point of view, to collect the leachate and subject it to biological and perhaps chemical treatment prior to discharge, at least during the initial stages of waste mineralization. This is indeed a common practice for sanitary landfills. The biological wastewater treatment effectively removes a substantial part of the readily degradable organic contaminants from the leachate, and the degradation/mineralization processes within the landfill will gradually reduce the pollution potential of the landfilled waste.

Inorganic, mineral waste types such as MSWI residues are not subject to biological degradation and mineralization processes (although they may be directly and indirectly influenced by biological processes occurring in residual organic matter or co-disposed organic waste). As shown earlier, these wastes will often generate leachates which initially have a relatively high concentration of inorganic salts and a moderate to low content of trace elements. As the leaching progresses with time both the salt content and the concentration of trace elements may gradually decrease to very low values (depending on pH and redox conditions). The content of organic substances in the leachate is often very low. The application of traditional sanitary landfilling techniques, i.e. installation of (multiple) bottom liners, collection and subsequent treatment of leachate at a biological wastewater treatment plant, to mineral wastes exhibiting such properties would generally not constitute an optimum or sustainable solution: The potential period of leaching may easily exceed the projected lifetime of the liners and the leachate collection system, and pumping and (particularly biological) treatment of the inorganic leachate are likely to be both energy consuming and ineffective. For such wastes, a strategy (controlled contaminant release), which limits the transfer of contaminants from the landfilled

material into the surrounding environment to an acceptable level by controlling the quantity and/or quality of the leachate produced but without collecting and treating it, may in some cases be more appropriate.

*4.2.3. Landfill design, operation and siting must be adapted to the admitted waste in such a manner that long term emissions become or remain environmentally acceptable*

Landfilling of inorganic, mineral wastes, including MSWI residues, may be operated in one or two stages. For mineral wastes with a high content of soluble contaminants (like some APC system residues), two-stage landfill operation may be necessary: An initial stage based on (possibly enhanced) leaching of contaminants with active environmental protection systems followed by a second stage, based on controlled contaminant release and requiring no active environmental protection systems. For mineral wastes containing only limited amounts of soluble contaminants, particularly trace elements, one-stage landfill operation based on controlled contaminant release with only passive environmental protection systems may be sufficient. For some mineral wastes which do not initially qualify for one-stage landfill operation, treatment prior to disposal may present an alternative to the first, active stage and render one-stage landfilling based on controlled contaminant release feasible. The treatment could, e.g., consist of extraction of soluble contaminants from the waste and/or stabilization with a binder. Extraction would reduce the total pollution potential of the waste whereas appropriate stabilization would also reduce the rate of release of contaminants substantially.

When the disposal strategy is based on controlled contaminant release, a sufficiently slow rate of transfer of contaminants from the landfill to the surrounding environment may be achieved either by ensuring that the concentrations of potential contaminants in the leachate are sufficiently low or by restricting the rate of generation and emission of leachate to an acceptable (low) level. Appropriately designed measures aimed at controlling the composition of the leachate (e.g. extraction and/or stabilization) are generally rather secure but they also tend to be relatively complicated and energy consuming. Passive environmental protection measures (e.g. geologically stable top covers and surface drainage systems) which are aimed only at restricting the quantity of leachate produced are technically much simpler but are, on the other hand, dependent on long-term durability and functionality of the systems. However, for passive systems, long lifetime expectancies are not necessarily unrealistic.

The transformation of active environmental protection systems into passive systems is required when a landfill based on two-stage operation passes from the active initial stage which may depend on collection and treatment of leachate to the final, passive stage which may depend solely on a controlled rate of production of leachate of sufficiently benign composition which is subsequently released into the environment. In this case an impermeable bottom liner may change from being a necessary instrument of one strategy to become an obstacle to another strategy. One way to avoid this could be to build fascines into the sides of the landfill, sufficiently high up to keep them inactive when a low level of leachate on top of the liner is



maintained during the active stage of landfill operation. Once the removal of leachate is discontinued, the level will rise and the fascines will provide conduits for dispersion of leachate into the surrounding soil/aquifer [30].

Proper siting is a crucial part of any disposal strategy, particularly if controlled release is envisaged from the start or during a later period of the existence of the landfill. Siting may strongly influence the criteria for acceptability of leachate in the surroundings. No disposal site should be placed on top of or immediately upstream of a valuable, sensitive aquifer or adjacent to a sensitive surface water body. However, if a saline (initial) leachate is expected, a location of a landfill near or at the coast of a not too sensitive sea/fjord/strait would appear suitable (if available) both in case of controlled contaminant release and leachate collection, treatment and discharge.

#### *4.2.4. Any landfill strategy must include consideration of the ultimate fate of the leachate and the residues remaining in the disposal site as well as derived effects of disposal and leachate management*

Regardless of whether the leachate is collected, treated and discharged or it is allowed to disperse into the surroundings according to the controlled contaminant release strategy, an energy and resources consumption analysis and an environmental impact assessment covering the entire pathway of the leachate and the entire leachate production period should always be conducted.

Derived effects such as the environmental impact of producing the energy necessary to pump and treat the leachate for the necessary period of time should be accounted for, and environmental impacts caused by the landfill but occurring elsewhere (e.g. at the outfall from a wastewater treatment plant which receives the leachate) should also be considered. Any environmental protection measures at a landfill should therefore be subjected to a lifecycle analysis prior to implementation.

## **5. Specific disposal strategies**

Disposal strategies may be categorized according to the prescribed management and intended fate of the leachate. Some of the specific strategies which may be relevant or have been applied to the disposal of MSWI residues are listed and summarized below:

- Total containment or 'entombment' (dry storage);
- Containment and collection of leachate;
- Controlled contaminant release;
- Unrestricted contaminant release.

Total containment and containment with leachate collection generally require active environmental protection systems, whereas the controlled contaminant release and unrestricted contaminant release strategies may require only passive environmental protection systems. Active environmental protection measures may be necessary during a first stage of landfilling in a number of cases but only strategies based on passive systems are sustainable in the long term.

### 5.1. *Total containment or entombment*

Total containment of MSWI residues will prevent any infiltration and percolation of water and, consequently, any generation and emission of leachate – as long as the containment system remains intact. The main weakness of a disposal strategy based solely on total containment is that the landfilled residues and hence the potential risk to the environment may remain virtually unchanged and at a maximum for a very long period, until the containment system finally fails and an uncontrolled plume of leachate may be released. This is particularly true for MSWI residue landfills equipped with (multiple) impermeable, artificial bottom and top liners and relying on zero discharge of leachate. The environmental risk is less pronounced for storage of untreated MSWI residues (such as APC residues) in old salt mines which, e.g., is practised in some parts of Germany. Underground storage is, however, a relatively costly solution which is not generally available and which should perhaps be reserved for truly hazardous waste. A total containment strategy may be acceptable for temporary, short-term storage of MSWI residues but it should always include plans or development of plans for appropriate final disposal or utilization of the residues, e.g. after treatment.

### 5.2. *Containment and collection of leachate*

A strategy based on containment with leachate collection and treatment corresponds to the traditional way of designing and operating a sanitary or MSW landfill. The leachate generated is contained by an impermeable or low permeable bottom liner, recovered and normally subjected to treatment prior to discharge to a surface water body. The rate of leachate formation may be reduced by a top cover of low permeability. Although commonly used, this strategy is not optimal for MSWI residues since it requires maintenance and operation for a period of time exceeding the expected lifetime of the vital environmental protection systems. Also, effective treatment of the MSWI leachate is likely to be difficult and energy consuming. Whereas the strategy appears unfit as a long-term solution to landfilling of MSWI residues, containment and collection of leachate may be applied as a first stage of operation, e.g. in connection with measures designed to enhance leaching. It must eventually be replaced by a second stage of operation, based on a more long-term oriented strategy.

### 5.3. *Controlled contaminant release*

The controlled contaminant release strategy implies that the release and emission of contaminants are maintained at an acceptable level by controlling the quantity and quality of the leachate generated within the landfill. The leachate is allowed to leak into the surroundings as it is formed. An assessment must always be carried out to ensure that the impact of the emitted leachate on the environment is acceptable. Both the quantity and quality of leachate depend upon the characteristics of the waste, the design and operation of the landfill and the climatic conditions.

Treatment of the waste may reduce both the contamination potential and the permeability. Installation of geologically stable, sloped top covers with surface drainage systems could ensure a very low rate of infiltration of precipitation and, consequently, a very low rate of release of contaminants from a disposal site in the short- and long-term. This concept requires proper siting. Since contaminants are being removed from the landfilled material, a continuous reduction of the contamination potential will occur. The controlled contaminant release strategy may represent a sustainable long-term solution to disposal of MSWI residues and should generally be preferred whenever possible. For some MSWI residues, a final controlled contaminant release stage of operation should be preceded by a short-term, active stage of operation based on a different strategy, e.g. enhanced leaching and containment and collection of leachate. This strategy currently is applied to MSWI residue disposal in some countries.

#### *5.4. Unrestricted contaminant release*

An unrestricted contaminant release strategy may simply be described as a landfill scenario where no precautions at all are taken to prevent or reduce the generation and emission of leachate. This strategy represents in most respects the opposite of the incapsulation strategy. The environmental impact will depend on the leaching characteristics of the landfilled waste as well as on local physical and climatic conditions and the vulnerability of the surrounding environment. Since the strategy implies total lack of control it is generally unacceptable for landfilling of MSWI residues except in cases where the leachate has reached ambient quality.

### **6. MSWI residues: Landfill strategies and leachate management**

Based on the data on characteristics and leaching properties of the MSWI residues and the discussion of disposal strategy, the feasibility of various disposal and leachate management options is briefly discussed in the following.

The disposal strategies applicable to mineral wastes such as MSWI residues and organic waste types are, as previously discussed, very different and generally totally incompatible, both in the short- and long-term. Co-disposal of MSWI residues and raw MSW is therefore generally not advisable. Different types of MSWI residues may also exhibit significant differences in behaviour when landfilled, and separate management and disposal of, e.g., bottom ash and APC residues is therefore recommended. The opportunity of applying different disposal strategies to different types of MSWI residues when appropriate is lost if bottom ash and APC system residues are combined.

#### *6.1. Bottom ash*

With proper siting (e.g. close to the sea or in an area without vulnerable aquifers), a disposal strategy based on controlled contaminant release seems appropriate and

should be pursued for landfilling of MSWI bottom ash. Pretreatment (e.g. washing or stabilization) may in some cases be required [31]. The possibilities for controlling the geochemical and biogeochemical conditions within a MSWI bottom ash landfill through ash quality requirements, ash treatment and landfill design should be investigated further. The rate of leachate production may be controlled partly through the design of the landfill. The construction of any bottom ash disposal site based on a controlled contaminant release strategy must be preceded by a careful environmental impact assessment which ensures that the rate of release of contaminants into the surrounding environment will not exceed an acceptable limit, neither in the short- nor in the long-term.

If, for some reason, a solution requiring containment and collection of leachate is to be chosen, either temporarily or indefinitely, it becomes necessary to manage and dispose of the leachate. MSWI bottom ash leachate is generally accepted at wastewater treatment plants as long as it does not constitute a major proportion of the total input to the plant. It has in some cases been necessary to reduce the pH of the leachate (by addition of sulfuric acid) and/or to elevate the redox potential from a reducing level to an oxidized level (e.g. by addition of hydrogen peroxide) prior to treatment at a wastewater treatment plant. In most cases no pretreatment has been necessary. The effect of biological wastewater treatment on the bottom ash leachate which contains mostly inorganic salts and little or no organic degradable matter is almost entirely restricted to dilution.

The various disposal options available for MSWI bottom ash, APC residues and combined ash, respectively, are summarized in Table 7.

### 6.2. APC residues (fly ash and acid gas scrubbing residues)

A sustainable disposal solution for the APC residues, particularly fly ash and residues from the dry and semidry acid gas scrubbing processes, must eventually be based on a controlled contaminant release strategy but it will almost certainly require extensive pretreatment of the residues. A two-stage treatment process involving removal and possibly recovery of the soluble salts (washing/extraction) followed by stabilization, vitrification or fixation of the remnant may be appropriate for this

Table 7  
Summary of MSWI residue disposal options

Disposal option	Bottom ash	APC residue	Combined ash
Total containment/dry tomb	No	Possible (e.g. salt mines)	No
Leachate containment and collection	Yes <sup>a</sup>	Yes <sup>a</sup>	Yes <sup>a</sup>
Controlled contaminant release	Yes <sup>b</sup>	May be <sup>b</sup>	May be <sup>c</sup>
Unrestricted contaminant release	No <sup>c</sup>	No <sup>c</sup>	No <sup>c</sup>

<sup>a</sup> If requirements for controlled contaminant release are not met (e.g. as a first stage of disposal).

<sup>b</sup> If requirements are met. May require prior or in situ treatment of the residues or may be second stage of disposal.

<sup>c</sup> Only after final storage criteria are met.

purpose [12, 13]. Considerable efforts are currently being spent on the development of such processes. In the meantime, disposal of APC residues are generally based on less sustainable strategies involving total containment/entombment or containment and collection of leachate. The same requirements concerning proper siting and design of a landfill and performance of an environmental impact assessment as mentioned above for bottom ash apply to a controlled contaminant release disposal strategy for APC residues.

The leachate produced at APC residue disposal sites based on containment and collection of leachate generally has a high concentration of inorganic salts and in some cases also relatively high concentrations of trace elements, particularly Pb and Cd. Such leachates are often accepted at municipal wastewater treatment plants without prior treatment, provided they do not constitute a major proportion of the total input to the plant. As mentioned for bottom ash leachate, dilution is likely to be the only beneficial effect of such a treatment. Leachates with a high content of heavy metals may have an adverse effect on the sludge from a biological treatment plant. If necessary, the concentration of several trace elements in the leachate (e.g. Cd and Pb, but not Cr) may be reduced substantially by a pretreatment including adjustment of pH and sedimentation/flocculation with TMT. This treatment may be relatively expensive if large amounts of leachate are produced. In most cases, removal of the inorganic salts from the leachate is not economically feasible or environmentally desirable.

### *6.3. Combined ash*

Although separate management and disposal of the different residue streams is believed to be technically and economically advantageous, both in the short- and long-term, the production of combined MSWI ash is still very much a fact of life, particularly in the USA. In principle, the disposal requirements for combined ash are similar to those described for APC residues. The proportion of residue requiring relatively stringent environmental protection measures when landfilled is increased substantially by the mixing of APC residue and bottom ash which also precludes utilization and renders pretreatment or in situ treatment of the residue more difficult and less efficient than it would be for separate ash streams.

### *6.4. Current MSWI residue disposal*

The need for implementation of sustainable MSWI disposal solutions such as those described above becomes more and more urgent as the dependency on MSW incineration continues to increase. Several practical problems related to sustainable disposal strategies remain to be solved, and a substantial research and development effort is needed.

The present MSWI residue disposal situation is not ideal. In the USA, disposal of combined ash is frequently managed using very stringent landfill design standards conforming to the leachate containment and collection or the total containment strategies. Both monofilling and codisposal with raw MSW occur. In Europe, the

strategies employed range from total containment through controlled contaminant release to unrestricted contaminant release. However, for bottom ash the prevailing disposal strategy in Europe is leachate containment and collection. The dominant strategy for APC residues appears to be total containment or placement in a 'dry tomb' [1]. While most of these landfills both in the USA and Europe are equipped with environmental protection systems which may be expected to be very effective in the short-term, the problems of sustainability and long-term effects have generally not been addressed. Some European countries have, however, in some cases allowed disposal of MSWI residues, primarily bottom ash, in landfills designed according to a controlled contaminant release strategy [1]. A successful implementation of this strategy would be consistent with the efforts to increase MSWI residue utilization.

## **7. Conclusions**

An overview has been given of the types of MSWI residues produced, their characteristics and their leaching properties. It has been established that short- and long-term behaviour of leachate is the most important potential environmental problem related to disposal of MSWI residues and other waste types. A disposal strategy should therefore primarily be expressed in terms of leachate management and fate.

A set of basic principles of waste disposal strategy has been presented. A sustainable waste disposal solution will require that: (1) each generation must take care of its own waste, (2) landfills are designed to minimize the required lifetime of active environmental protection systems, (3) any disposal strategy reflects the inherent properties of the waste, (4) landfill design, operation and siting are adapted to the admitted waste in such a manner that long-term emissions of leachate become or remain environmentally acceptable, and (5) any waste disposal strategy considers the ultimate fate of the leachate and the residues remaining in the disposal site as well as derived effects of disposal and leachate management.

Application of these principles to MSWI residues indicates that a sustainable disposal solution for MSWI bottom ash and APC residues, at least in the final stage, should be based on a controlled contaminant release strategy, i.e. a strategy which allows the leachate to leak into the surroundings at an environmentally acceptable rate. The rate of production and emission of leachate may be controlled by geologically stable surface covers and run-off systems which do not require maintenance or input of energy. It may be necessary to subject the MSWI residues, particularly the APC residues, to pretreatment (e.g. washing and stabilization) prior to disposal in order to reduce the amount of potentially leachable salts and trace elements which are the major contaminants of concern. Disposal of bottom ash is considered less problematic than disposal of APC residues. MSWI residues should generally be monofilled, and different types of residues (e.g. bottom ash and APC residues) should not be mixed.

If a controlled contaminant release strategy is applied successfully to MSWI residues, no collection and treatment of the leachate produced should be necessary.

While the necessary technical solutions are being developed or when, for any other reason, disposal methods requiring containment and collection of leachate are being used, the leachate may need pretreatment prior to discharge to, e.g., the sewage system or directly to a wastewater treatment plant. Such pretreatment may consist of adjustment of pH and/or redox potential and/or removal of heavy metals. The main effect of treatment of the leachate from MSWI residues which primarily contain inorganic salts is merely dilution.

## References

- [1] A.J. Chandler, T.T. Eighmy, J. Hartlen, O. Hjelmars, D.S. Kosson, S. Sawell, H.A. Van der Sloot and J. Vehlow, An international perspective on characterization and management of residues from municipal solid waste incineration, Summary Report of the IAWG, c/o Compass Environmental Inc., 2253 Belmont Court, Burlington, Ontario, Canada, 1994.
- [2] TA-Siedlungsabfall, Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Bonn, 1993.
- [3] Miljøstyrelsen, Handlingsplan for affald og genanvendelse 1993–97, Miljøministeriet, København, 1992.
- [4] US EPA and CORRE (Coalition on Resource Recovery and the Environment), Characterization of Municipal Waste Combustion Ash, Ash Extracts, and Leachates, EPA 530-SW-90-029A, Washington DC, 1990.
- [5] O. Hjelmars, H. Thomassen and H. Højmark, Restprodukter fra røggasrensning ved affaldsforbrænding I: Udredning, Miljøprojekt nr. 146, Miljøstyrelsen, København, 1990.
- [6] H.W. Rasmussen, O. Hjelmars, A.Ø. Knudsen, T. Christiansen and H. Birch, Sambehandling af restprodukter fra affaldsforbrænding. Fase I. Arbejdsrapport fra Miljøstyrelsen, Miljøstyrelsen, København, 1993.
- [7] J. Vehlow, Heavy metals in waste incineration, Presented at DAKOFA Conf. Waste Incineration under New Conditions, Copenhagen, 6 September 1993.
- [8] J. Hartlén and P. Elander, Residues from waste incineration – chemical and physical properties, SGI Varia 172, Statens Geotekniska Institut, Linköping, Sweden, 1986.
- [9] O. Hjelmars, in: Proc. Internat. Workshop on Municipal Waste Incineration, NITEP, Montreal, Canada, 1987, p. 287.
- [10] O. Hjelmars, Stofudvaskning fra flyveaske fra affaldsforbrændingsanlæg. Rapport til Miljøstyrelsen, Vandkvalitetsinstituttet, Hørsholm, Denmark, 1993.
- [11] O. Hjelmars, K.J. Andersen, J.B. Andersen, E.A. Hansen, A. Damborg, E. Bjørnestad, A.H. Knap, C.B. Cook, S.B. Cook, J.A.K. Simmons, R.J. Jones, A.E. Murray, M.J. Lintrup, H. Schrøder and F.J. Roethel, Assessment of the environmental impact of incinerator ash disposal in Bermuda, Final Report, Prepared for Ministry of Works & Engineering, Hamilton, Bermuda, By the Water Quality Institute, Hørsholm, Denmark, 1993.
- [12] O. Hjelmars, in: Proc. ISWA Specialized Conf. on Incineration and Biological Waste Treatment, Amsterdam, The Netherlands, 1–3 September 1992.
- [13] O. Hjelmars, Restprodukter fra røggasrensning ved affaldsforbrænding II: Eksperimentelle undersøgelser, Miljøprojekt no. 193, Miljøstyrelsen, København, 1992 (in Danish, English summary).
- [14] S. Kullberg, A.-M. Fällman and A. Höjlund, Stabilisering och deponering av røggasreningsprodukter från sopförbränning, Bränsleteknik 370, Stiftelsen för värmeteknisk forskning, Stockholm, 1989.
- [15] R. Klicius, A. Finkelstein and D.J. Hay, in: (L. Andersen and J. Møller, Eds.), Proceedings of the 5th International Solid Wastes Conference, Volume I, Copenhagen, 1988, p. 325.
- [16] Miljøstyrelsen, Unpublished results, Strandgade 29, Copenhagen, 1993.
- [17] S.E. Sawell and T.W. Constable, The National Incinerator Testing and Evaluation Program: The influence of incinerator design on ash characteristics. in: W.H. Chesner and T.T. Eighmy (Eds.),

- Proc. of the 3rd Internat. Conf. on Ash Utilization and Stabilization (Ash III), Arlington, Virginia, USA, November, 1990, Durham, 1991, p. 97.
- [18] S.E. Sawell, T.W. Constable and R. Klicius, The National Incinerator Testing and Evaluation Program: Characterization of residues from a Modular municipal waste incinerator with lime-based air pollution control, IP-101, Environment Canada, Ottawa/Burlington, Ontario, 1989.
- [19] D.O. Reimann, Abwasserbehandlung aus Müllverbrennungsanlagen, Müll und Abfall, 19 (1987) 1.
- [20] O. Hjelmars, in: Proc. WASCON '91, Environmental Implications of Construction with Waste Materials, Maastricht, The Netherlands, 1991.
- [21] N. Thygesen, F. Larsen and O. Hjelmars, Risikoscreening ved nyttiggørelse og deponering af slagger, Miljøprojekter 203, Miljøstyrelsen, København, Denmark, 1992.
- [22] R.N.J. Comans, H.A. van der Sloot and P.A. Bonouvie, in: Municipal Waste Combustion, Proc. Internat. Specialty Conf., Williamsburg, Virginia, March 1993, A&WMA, Pittsburgh, Pennsylvania, 1993, p. 667.
- [23] D.S. Kosson, H.A. van der Sloot and T.T. Eighmy, *J. Hazard. Mater.*, this issue.
- [24] O. Hjelmars, in: Proc. Internat. Conf. on Municipal Waste Combustion, Hollywood, Florida, 1989, pp. 3B1–3B19.
- [25] H.A. van der Sloot, R.N.J. Comans, T.T. Eighmy and D.S. Kosson, in: Proc. Internat. Recycling Conf., Berlin, 1992.
- [26] L. Andersen and J. Boll, Udvaskning fra røggasrensningsprodukter fra affaldsforbrændingsanlæg, Pilotskalaforøg, I: Udvaskning fra slagger, jord og affald, ATV-Komiteen vedrørende grundvandsforurening, Lyngby, Denmark, 1994, p. 85.
- [27] R.K. Cambotti and H.K. Roffman, Municipal Waste Combustion Ash and Leachate Characterization. Monofill – Fifth Year Study, Woodburn Monofill, Woodburn, Oregon, Report prepared by AWD Technologies, Pittsburgh, Pennsylvania, 1993.
- [28] H. Belevi and P. Baccini, *Manage. Res.*, 7 (1989) 43.
- [29] O. Hjelmars, L.M. Johannessen, K. Knox, H.-J. Ehrig, J. Flyvbjerg, P. Winther, and T.H. Christensen, Management and Composition of Leachate from Landfills, Commission of the European Communities, Contract No.: B4-3040/013665/92, Final Report, 1995.
- [30] L.M. Johannessen, O. Hjelmars and J. Riemer, 1993, in: T.H. Christensen, R. Cossu and R. Stegmann, (Eds.), Proc. Sardinia '93, IV International Landfill Symp., S. Margherita di Pula, Italy, 11–15 October 1993, CISA, Cagliari, Italy, 1993, p. 1745.
- [31] H. Belevi, D.M. Stämpfli and P. Baccini, *Waste Manage. Res.*, 10 (1992) 153.