THE MANAGEMENT OF RESIDUES FROM THERMAL PROCESSES

1 INTRODUCTION

1.1 Study Background

The combustion of municipal solid waste (MSW) and refuse derived fuel (RDF) in Energy from Waste (EfW) facilities is a widespread practice with a trend towards increased growth in the International Energy Agency (IEA) and International Solid Waste Association (ISWA) member countries. The management of residues arising from the combustion of waste is probably the greatest technical issue affecting the development of MSW and RDF thermal treatment technologies world-wide. Current practices involve treatment, disposal and/or utilisation of the residues. The emphasis of these waste residue management practices is dependent on the local legislation. In the majority of IEA member countries, the current preferred option is ash utilisation that has the potential to generate an income that could offset disposal costs and taxes where levied. If markets cannot be found for the residues, safe and environmentally acceptable methods for the disposal of waste combustion residues must be available. This is becoming increasingly important in the light of new European legislation on waste minimisation and, for example, in the UK with the introduction of the new tax incentives.

In 1994 the International Ash Working Group (IAWG)[1] completed a comprehensive study on the management of residues. Since that time, the IEA Bioenergy Thermal Conversion Activity has kept a watching brief on the development of residue management in member countries. The IEA have identified the need to update the records of current practice and report on the prospects for the utilisation, treatment and disposal of residues.

1.2 Objectives

The overall objective of this project has been to develop the work carried out by the IAWG, to update it (particularly with reference to current practice in management of solid residues generated from the thermal treatment of MSW and RDF) and to report on the future trends and prospects for the utilisation, treatment and disposal of residues. Specifically this has involved:-

1. Collation of data on the nature and characteristics of residues produced from the thermal treatment of MSW and RDF and their classification in terms of United Kingdom (UK) and European Union (EU) waste management regulations.

2. Review of current practice in residue management, future trends and the focus of research and development activity, reporting in particular on any barriers to the development of beneficial residue utilisation.

3. Review of residue markets and economics of residue processing, re-use and landfill disposal.

1.3 Data Collation Programme

In order to fulfil the objectives of the study a comprehensive questionnaire was compiled, with co-operation from the UK Energy from Waste Association (EWA) and the IEA, and sent to plant operators in IEA and ISWA member countries (Austria, Belgium, Canada, Finland, France, Hungary, Japan, Netherlands, Norway, Spain, Sweden and the UK). The questionnaire requested information on the nature and characteristics of combustion residues, the current practice in residue management, barriers, future trends and focus of research and development activity.

The response from the plant operators was generally good. However, not unexpectedly, the amount of data provided was variable. For example, there appears to be some conflict over confidentiality issues for certain categories listed in the proforma, such as the economics of ash residue recovery, re-use and disposal. The data provided by the plant operators for the IEA/ISWA member countries was collated and is presented in Volume II of this report.

In order to provide an overall view of the management of residues from thermal processes in IEA/ISWA member countries, data from other sources and other countries has been sought to supplement this report.

1.4 Report Structure and Outline Content

The report has been structured to give an overall review of current practices in the management of residues from thermal processes, to detail the finding of the data collation study and to give specific examples of waste residue practices. The report begins with an overview of waste management policy and performance in IEA and ISWA member countries. Sources of waste, combustion technologies and ash residue types are outlined in Section 3. This is followed by details of the physical and chemical characteristics of ash residues and their categorisation as special or non-special waste (Sections 4 and 5). Sections 6, 7, 8 and 9 review the current status of residue management, and cover practices and costs for treatment, recovery and re-use applications and for disposal. The incentives and barriers for residue utilisation are reviewed in Section 10, whilst Section 11 outlines the focus of research and development activities in waste ash residue utilisation. Conclusions and recommendations drawn from the report are listed in Section 12 of the text. General details of experience for the various countries are given in the relevant sections, whereas specific case studies on re-use applications for ash residues from MSW treatment facilities (known as MSW ash residues) are given in Appendix I.

Data on management of ash residues provided by the EfW facilities that responded to this study is reported separately, a copy of which is available from the UK EWA.

2 OVERVIEW OF WASTE MANAGEMENT POLICY

2.1 Waste Management Strategy

In September 1989, the European Union (EU) published a Community Strategy for Waste Management covering waste prevention, re-use, recycling, energy recovery, waste disposal, regulation of waste shipment and clean-up of contaminated sites. This document, which was supported by the EU Council in a Resolution of May 1990, was used as a basis for introducing newer and stricter legislation in many of the IEA member countries.

The UK Government built on the EU's waste strategy in its own approach to sustainable waste management in England and Wales, set out in 1995. The aim of the strategy is to focus attention on techniques and methodologies, which can be used to manage waste in a more sustainable way. Principal targets for achieving this aim are:

- to reduce the amount of waste produced; in particular, to reduce the proportion of controlled waste going to landfill from 70% to 60% by 2005;
- to make best use of the waste that is produced; in particular, to recover value from 40% of municipal waste by 2005; and
- to choose waste management practices which minimise the risks of environmental pollution and harm to human health; in this context, to set a target before 1999 for overall waste reduction.

The overall thrust of the UK Government's waste strategy is to increase the proportion of waste being dealt with by waste management options towards the top of the hierarchy shown in Table 2.1.

The majority of IEA/ISWA member countries are also introducing stricter legislation and making considerable efforts to reduce the amounts of waste being landfilled through recycling and treatment in Energy from Waste (EfW) facilities. In July 1999, the EU mandated reductions by member nations in biodegradable waste charged to landfills using their 1995 output as the benchmark. They are, by July 16, 2004, 25%; by 2007, 30%; and by 2014, 35%. However, the EU will re-examine in 2012 whether the 2014 target can be achieved. In anticipation of this, the new legislations introduced in Germany and the Netherlands, entitled "Ordinance for Residential Waste (TA Siedlungsabfall)"[2] and "National Environmental Policy Plan-II", were aimed at enforcing a restriction on the amount of organic material entering landfills by 1999 and 1996 respectively. Table 2.2 shows three estimates for waste generation and management over the next decade compiled by the Dutch Waste Planning Council[3].

In Germany, landfill legislation requires ash residues from EfW treatment plant to meet a loss on ignition criteria. Although both governments hope that recycling will divert a large portion of materials from landfill, there is also an emphasis on energy recovery, and existing EfW capacities will have to increase to keep pace with the waste diversion targets.

The new EU Directive on Landfill, also leads to a reduction in the amount of waste going to landfill[4]. The proposed Directive requires all wastes to be treated before being landfilled and co-disposal (the mixing of hazardous waste with MSW in the same landfill) to be phased out. Costs for landfill disposal must cover the costs of closing the landfill site as well as management, and also must cover at least 50 years of care after closure of the site. In an effort to reduce the EU's total methane emissions, the revised proposal aims to reduce the quantity of biodegradable MSW sent to landfills; in addition, methane from both new and existing landfills would have to be collected and used, or flared off.

Priority	Options	Explanation/Benefits
1	Reduction	Reduction of waste at source through technological and design improvements (e.g. improved product lifetime) and reduction of use of consumables. Consistent with economic sustainability (Priority to be given to the minimisation of special waste, with some target materials to be eliminated entirely from the waste stream).
2	Re-Use	Putting objects back into use (e.g. bottles, car and machinery components) through designing for re-use for the same function or finding a secondary use (e.g. use of old tyres as boat fenders).
3	Recovery - Recycling	Putting materials back into use (e.g. glass, plastics, paper, cans etc.). Potential for considerable saving in energy consumption and reduced emissions to atmosphere. Economic incentive to recycle will improve following Government policy to make disposal to landfill more expensive.
	- Composting	Processing organic materials to produce soil additives/growing media reducing the demand for artificial fertilisers and for natural resources. Aerobic composting of waste lessens potential emissions of greenhouse gas, methane, from landfill sites.
	- Energy Recovery	Four main approaches are:- • combustion with heat recovery (EfW) • processing selected waste for use as a fuel • burning methane produced in landfill sites • controlled anaerobic digestion of sewage or municipal waste to produce methane for burning. Energy recovery is five times more efficient from waste combustion than from collecting and burning landfill gas. Combustion reduces waste volume for final disposal by about 90%. However, there can be toxic emissions and residues, requiring special precautions, and it remains generally more expensive than landfill, despite increasing landfill costs.
4	Disposal	Environmentally sound techniques, but with no benefit derived from the materials. Increases in landfill tax will reduce its attractiveness. Disadvantages of landfill include loss of amenity at the site and on the transport routes, the release of methane into the atmosphere and the potential for leaching of harmful substances into ground water supplies. Other disposal options include combustion without energy recovery and chemical destruction or permanent storage of specialised wastes.

Table 2.1 Waste Management Hierarchy

YEAR	TOTAL WASTE	REDUCTION THROUGH		BALANCE	
		PREVENTION	RECYCLING	INERT	COMBUSTIBLE
1993	28	3	11.7	5.7	7.6
2005 (Policy)	31	3.1	19.7	3.1	5.1
2005 (Negative)	31.5	2.2	18.2	4.3	6.8
2005 (Predicted)	35	3.8	22.9	3.1	5.2

Table 2.2 Projected Waste Generation Quantities in the Netherlands to 2005 ***(Tg/y)***

2.2 Waste Management Performance

Current estimates for the waste management practices for MSW in various countries world-wide are provided in Table 2.3 and shown graphically in Figure 2.1[5]. In the UK, landfill is still by far the most common waste management option used by municipalities, with only 10% utilised for energy recovery and 5% recycled. This compares with Switzerland, where 42% of the national waste output is recycled and 47% combusted, and Japan where 74% of the waste material is combusted and 5% recycled. The reasons for the different patterns of disposal in other countries reflect different decisions made by governments regarding funding, availability of landfill and geological conditions, and differing pressures to promote recycling and recovery.

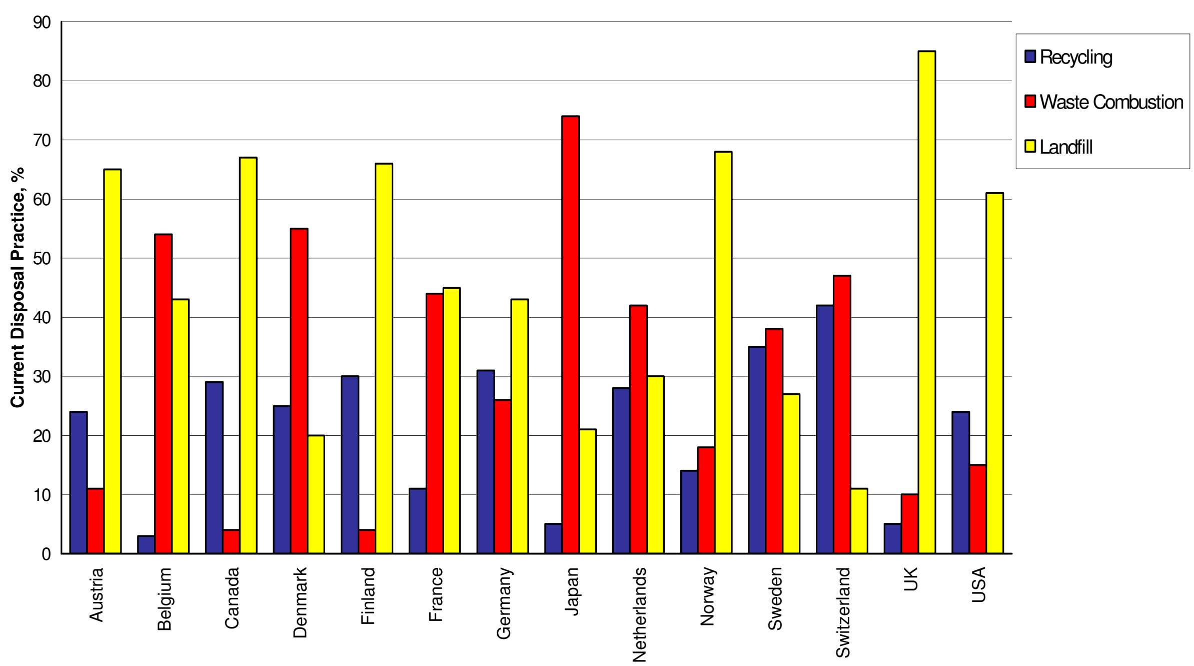


Figure 2.1 Waste Management Practices for MSW

Country	Current Disposal (%)			Comment
	Recycling[1]	Waste Combustion[2]	Landfill	
Austria	24	11	65	Combustible waste to landfill banned from 2004.
Belgium	3	54	43	Aims to ban landfilling of combustible waste.
Canada	29	4	67	Aims to reduce reliance on landfill.
Denmark	25	55	20	Ban on combustible waste to landfill being implemented.
Finland	30	4	66	Policy to increase combustion and reduce landfill.
France[3]	11	44	45	Combustible waste to landfill banned from 2002, expect combustion to rise to 57% and recycling to 23%.
Germany[3]	31	26	43	Combustible waste to landfill banned from 2004.
Japan	5	74	21	Upgrading existing facilities for power generation.
Netherlands	28	42	30	Combustible waste to landfill already banned.
Norway	14	18	68	Aims to ban landfilling of combustible wastes.
Sweden[4]	35	38	27	Policy to increase combustion and recycling.
Switzerland	42	47	11	Combustible waste to landfill banned from 2000.
UK[3]	5	10	85	Recycling target 25% and Recovery target of 40%. New waste strategy under preparation.
USA	24	15	61	No immediate changes foreseen.

[1] Includes composting; [2] Primarily with energy recovery [3] 1999 values (ref.[6]) [4]1998 values (ref.[7])

Table 2.3 Comparison of MSW Management Practices[8]

3 THERMAL PROCESS RESIDUES; SOURCES, TECHNOLOGIES AND TYPES

3.1 Waste Sources

The majority of waste that is treated by EfW combustion in the IEA/ISWA member countries is Municipal Solid Waste (MSW) with little or no pre-processing. MSW is a heterogeneous resource consisting of the discarded wastes from domestic and institutional sources. In certain countries MSW also includes industrial and general trade waste. In others commercial waste is collected separately. Estimates of the composition of MSW streams in North America and a number of European countries are given in Table 3.1[9]. The physical characteristics and composition of MSW in the UK are illustrated in Figure 3.1.

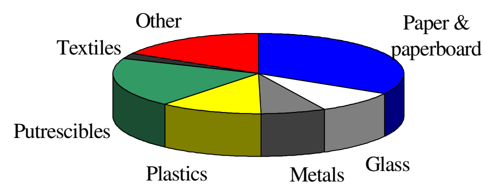


Figure 3.1 Typical Characteristics of MSW in the UK

MSW can be sorted to recover metals, glass and other products. This concentrates the combustible components of MSW as organic materials and paper to give a fuel, which is referred to as Refuse Derived Fuel (RDF). This sorted material has a more uniform size, improving the fuel handling characteristics.

Other waste sources include clinical waste. Clinical waste is infectious or hazardous material, which might pose a risk to public health and is subjected to separate control (under the Special Waste Regulations 1996)[10].

Estimates for waste generation quantities in Europe and America are also provided in Table 3.1. The US EPA suggest that over 200 million tonnes (Mt) of municipal solid waste are generated in the USA in 1994. This equates to around 2 kilograms/person/day. Comparable levels of waste generation per capita were reported for Canada, the Netherlands, Sweden and the UK. Estimates for Germany were low (1.45 kg/day) as the German waste paper generation data provided was post diversion for recycling, whereas the data for the other countries refers to pre-diversion.

3.2 EfW Technologies

Energy from Waste (EfW) is the combustion of waste under controlled conditions in which the heat released is recovered for a beneficial purpose. This may be to provide steam or hot water for industrial or domestic users, or for electricity generation. Combined heat and power (CHP) EfW

CATEGORY	CHARACTERISTIC	NORTH AMERICA		EUROPE				
		Canada	United States	Germany	France	The Netherlands	Sweden ++	United Kingdom++
Year of Data Collection		1994	1994	1992	1990	1993	1994	1994
Waste Tonnage (Tg/a)	Paper & paperboard	8.49	77.8 - 81.3	8.65+	10.2	3.74	1.2	6.64
	Glass	0.97	13.3 - 13.7	5	4.08	0.41	0.18	1.86
	Metals	3.94	15.8 - 17.1	1.69	1,7	0.12	0.11	1.46
	Plastics	1.76	19.3 - 19.8	2.65	2.04	0.5	0.22	2.24
	Wood		13.7				0.03	
	Putrescibles**	7.7		11.75	8.5	3.6		4.04
	Food		13.8 - 14.1				1.31	
	Yard waste		30.6.. 32.8					
	Textiles			0.65			0.06	0.42
	Other	2.05	18.7	13.14	7.48	2.54	0.16	3.34
	Total	**22.3**	**206 -209**	**43.5**	**34**	**11**	**7.2**	**41.1**
Per Capita Generation (kg/day)		2.02	2.04	1.45	1.6	1.93	2.2	1.95
Percentage Composition (%)								
	Paper & paperboard		37.6-38.5	19.9	30	31.2	37.4	33.2
	Glass		1.8-6.6	11.5	12	3.4	5.5	9.3
	Metals		4.2-8.3	3.9	5	1	3.4	7.3
	Plastics		9.0-9.6	6.1	6	4.2	6.9	11.2
	Wood		6.0 – 6.6				1	
	Putrescibles* *			27	25	30	40.9	20.2
	Food		5.0-6.7					
	Yardwaste		8.9-15.9					
	Textiles			1.5			1.9	2.1
	Other		7.0-12.0	30	22	21.1	5	16.7

*Notes: 1 ** = combined wood. food and yard waste; 2. + = post recycling numbers; 3. ++ = reflects household waste only*

Table 3.1 Summary of Municipal Solid Waste Data for North America and Europe

combustion provides both heat and electricity. The fuel value (calorific value) of MSW is about one-third that of coal: as a rough guide, for every 100,000 tonnes of EfW capacity about 7 MW of electricity could be exported to the grid, enough to meet the needs of about 11,000 homes.

There are many EfW combustion manufacturers around the world. While each system has some unique features, combustion systems can be divided into two broad categories based on the fuel characteristics:

- Mass burn – the as-received MSW, with the exception of oversized material (appliances and furniture etc.), is fed directly into the furnace and burned on a grate or hearth without pre-treatment such as size reduction, shredding or material separation prior to burning.

- Refuse derived fuel – the as-received MSW is usually shredded to reduce the size and sorted to remove non-combustibles to produce what is known as refuse derived fuel (RDF); and then burned in a suspension or grate fired furnace.

A third category of EfW technology, based on pyrolysis of the waste, combustion of the derived fuel gas and melting of the non-combustible material, is being developed in a number of countries. Whilst not strictly based on direct combustion of the waste, a brief description has been included in this report.

3.2.1 Mass burn

The most widely deployed energy from waste (EfW) process is mass burn with either wet, dry or semi-dry gas cleaning systems. In mass burn facilities, waste is burned on a moving grate in a boiler with little or no pre-processing (Figure 3.2).

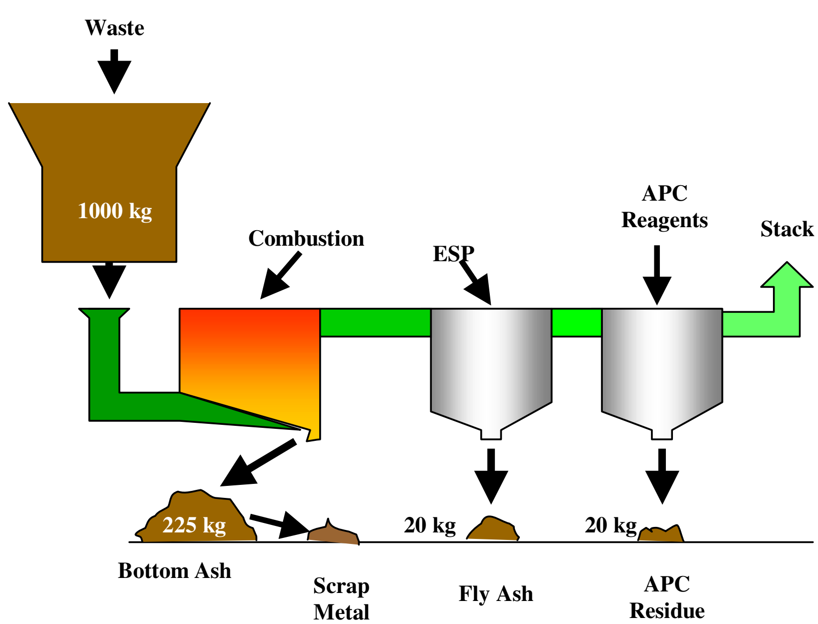


Figure 3.2 Waste Residue Streams in a Mass Burn EfW Combustion Facility

The boiler and grate system are large and robust in order to cope with most articles in the waste stream. The burned out residue falls from the end of the grate into a water quench bath, where it is removed by mechanical means. The ash (bottom ash) is de-watered and ferrous metal magnetically separated from the bottom ash and sold for scrap prior to storage, disposal or utilisation. After the heat from the hot combustion gases has been recovered in the boiler, the gases are cleaned to remove fine particulates (fly ash), acid gases and organic compounds. In IEA member countries, there is a diversity of installed air pollution control (APC) equipment in EfW facilities. Some EfW facilities remove fine fly ash particles from the hot combustion gases using electrostatic precipitators prior to wet scrubbing by alkaline solvents to remove the acid gas components and flue gas condensation/reaction products. Units that utilise dry or semi-dry scrubbing systems (involving injection of an alkaline powder as a slurry) generally utilise fabric bag filters downstream of the scrubber systems to remove fly ash and other residue fractions (scrubber residues, condensation/reaction products). Additional APC measures, e.g. use of high surface area carbon-based sorbents are seeing increased use for mercury control and reduction of organic emissions[11]. The scrubber residues and bag filter dust are known as the air pollution control (APC) residues and are often combined with the fly ash. Both the fly ash and APC residues (scrubber residues, bag filter dust and other sorbent residues) contain potentially harmful material, such as heavy metals or traces of micropollutants and are often combined prior to storage in air tight systems. Fly ash and APC residues are usually conditioned by adding water prior to transport for landfilling.

Mass burning technologies were developed in Europe at the turn of the century and have undergone substantial advancement over the past 20 years. By installing advanced combustion control systems, altering the configuration of the furnace and the location of the air injection ports, the combustion performance of these systems has been greatly improved. These improvements have lowered emissions of trace organics and raised the thermal efficiency of the furnaces. In addition, some facilities now process waste (e.g. by mixing) before feeding it to a mass burn plant and consider the extra cost to be warranted because the system runs more smoothly.

A novel mass burning technology developed in Switzerland is based on the conversion of bulky waste materials in a water-cooled inclined grate with combustion of the gas from the grate incinerator, together with liquid, slurry and fine particle waste, in a secondary circulating fluidised bed combustion chamber[12]. Dry flue gas cleaning systems, based on lime injection and activated carbon are an integral part of the system to ensure environmental emissions are minimised.

3.2.2 Refuse derived fuel

An alternative approach to mass burn systems is to first sort the household waste to remove recyclable materials (e.g. magnetic separation of the ferrous component) and wet putrescible materials. The combustible material is then shredded and burned as refuse derived fuel (RDF). Further processing can be used to remove glass, grit, sand, certain plastics and aluminium materials if desirable. Air classifiers or rotary drums may also be used to further process the fuel product by removing additional non-combustible materials. During the processing the material is thoroughly mixed improving its homogeneity. The level of processing required is mainly dependent on the specific system used for incineration of the RDF. In IEA member countries, the RDF fuel is generally fired in fluidised bed or grate incinerators. The grate fired systems are of similar design to the mass burn plant (section 3.2.1) and, in general, the level of processing is less than that required for fluidised bed technologies where physical treatment, such as milling, is always necessary.

Fluidised bed combustion (FBC) technology has been adapted to fire RDF materials and has shown promise in both Europe and Japan, although the installed size of these units tends to be smaller than conventional European mass burn furnaces[9]. In FBC systems, the RDF is fed to the reactor and burned in a fine inert material, such as sand, fluidised by air blowing upwards through it. Flue gas cleaning is typically via cyclone separators for the removal of larger particles; limestone injection into the combustion chamber or lime injection into the flue gas for sulphur dioxide (and chlorine) abatement; and bag house filters for removal of the finer particulate materials (Figure 3.3).

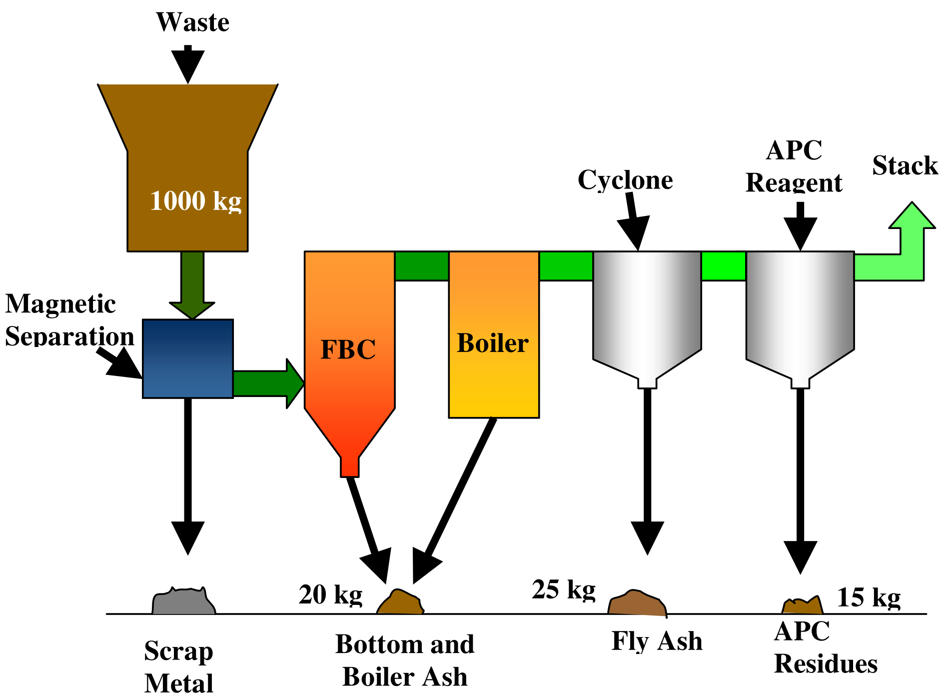


Figure 3.3 Waste Residue Streams in a FBC EfW Combustion Facility

Within the FBC plant, a drum sieve is used to separate the bottom ash from the sand particles. Although this sieve is not particularly efficient, it does allow much of the sand to be recycled to the fluidised bed. The bottom ash removed from the base of the FBC is not quenched and still contains a high proportion of sand particles from the fluidised sand bed. It is mixed with boiler dust before leaving the plant for landfilling or re-use. The flue gas cleaning residue streams consist of cyclone dust (fly ash) and APC residues (desulphurisation residues and bag house filter dust). These streams are often combined prior to disposal.

3.2.3 Pyrolysis/melting process

An alternative EfW technology, still under development, is based on pyrolysis of the waste to produce a fuel gas and melting of the non-combustible residue (Figure 3.4). Drying, pyrolysis and melting of waste is carried out step wise in a vertical furnace. The pyrolysis gas produced is burnt in the combustion chamber. Heat is recovered from the flue gas in a waste heat recovery generator (WHRG) and used in a steam turbine to produce electric power. The cooled flue gas is cleaned (nitrogen and sulphur abatement technologies and bag house filters for removal of fine particulates) prior to release to atmosphere. The technology was derived from the field of iron and steel technology and requires coke to operate. The high temperatures generated in the vertical furnace melt the non-combustible residues (ash, metal and glass), which is discharged from the furnace and separated into slag and iron. Bag filter dust, which contains fine dust particles and flue gas cleaning residues, is treated prior to disposal.

3.2.4 IEA/ISWA member countries

No data was available on the waste processing undertaken prior to incineration and, for this report, the EfW plants have broadly been categorised into three 'technologies', namely mass burn, FBC and pyrolysis/melting. The 'mass burn' technology refers to grate incinerators mainly firing waste, which has received little or no pre-processing.

Table 3.2 gives an overview of the numbers of EfW facilities which responded to this study, together with typical annual tonnages of waste processed and annual production of solid residues. This study confirms that the most common technology used for processing waste is a traditional mass burn plant with pollution abatement to remove fine particulates. Respondents also included FBC plants in Austria, Japan, Spain, Sweden and UK and two pyrolysis/melting processes in Japan. Typical capacities

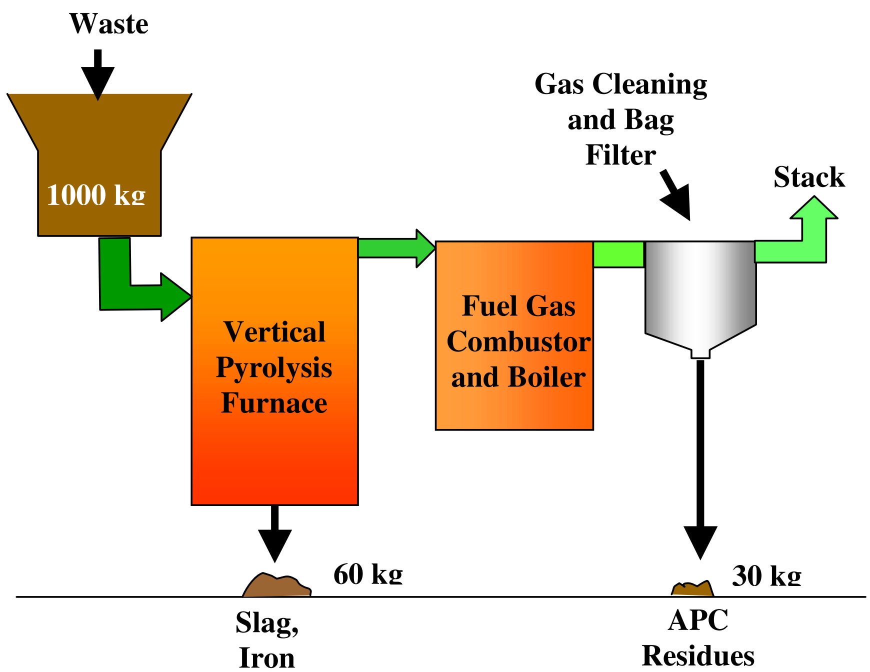


Figure 3.4 Waste Residue Streams in a Pyrolysis and Melting Process

for mass burn plant range from 100,000 to over 250,000 tonnes/year throughput. This compares with typical annual tonnage capacities of 100,000 to 150,000 for FBC EfW plants and around 15,000 tonnes per year for development scale pyrolysis/melting processes. A brief description of EfW capacities in Sweden and the UK is given below.

Swedish Experience

Currently, there are 22 EfW plants with a total of 31 boiler units in operation in Sweden[13]. The boilers range from 1 to 58 MW thermal capacity. Most units are conventional mass burn systems but 9 units are FBC plants. Together the plants treat almost 2 million tonnes of waste (MSW and industrial). The energy produced in 1998 was 5.7 TWh. Almost all of this (97-98%) was utilised as electricity or district heating. All except for 3 plants are owned and operated by the municipalities, 2 are owned and operated by private companies and 1 is owned by the municipality and operated by a private company.

Country	EfW Technology	No. of Plants	Plant Capacity (typical annual tonnage per plant)				Solid Residue Production (tonnes/year/plant)			
			MSW	RDF	Clinical Waste	Light Commercial	Bottom Ash	Fly Ash	APC Residues	Molten Slag
Austria	Mass Burn	2	180,000-255,000	-	-	-	50,000-58,000	3,000-5,000	200-350	200-6,300 (scrap iron)
	FBC; Rotary Kiln	1	270,000	11,500	-	-	15,500	17,500	2,000	470 (scrap iron)
Belgium	Mass Burn	2	110,000	-	-	-	20,000	2,000	3,000	-
Canada	Mass Burn	1	240,000	-	-	-	44,000	-	7,000	-
Finland	Mass Burn	1	50,000	-	-	-	11,000	2,200		-
France	Mass Burn	110 (average data)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Hungary	Mass Burn	1	340,000	-	-	-	115,000	13,000	-	-
Japan	Mass Burn	5	18,000 - 99,000	-	-	-	2,000 - 6,000	-	19,000	-
	FBC	1	-	-	-	-	-	-	-	-
	Pyrolysis/melting	2	7,500 - 19,000	-	-	-	-	-	40	150
Netherlands	Mass Burn	11	1,150,000-41,000	240,000-400,000	-	-	260,000-10,000	90,000 (total)	-	-
Norway	Mass Burn	3	70,000 - 130,000	-	750 - 1,300	12,500 - 30,000	13,000 - 25,000	1,500 - 3,000	300 - 400	-
Spain	Mass Burn	5	35,000 - 440,000	54,000	-	-	7,000 - 60,000	1,000 - 11,000		-
	FBC	1	440,000	270,000	-	-	13,500	17,000	10,000	-
Sweden	Mass Burn	10	70,000 - 380,000	22,000	10 - 2,000	25 - 25,000	3,000 - 80,000	250 - 24,000		-
	FBC	2	13,000	20,000	-	6,000	-	3,000		-
UK	Mass Burn	6	70,000-410,000	-	10,000	21,000	18,000 - 120,000	2,000 - 16,000		-
	FBC	1	-	60,000	-	-	1,000	-	20,000	-

Table 3.2 Response of EfW Facilities in IEA/ISWA Member Countries

UK Experience

There are currently 12 operating EfW plants in the UK, most of which are based on mass burn technology. The SELCHP (South East London Combined Heat and Power) plant in Lewisham which opened in 1994 was the first of the totally new generation of EfW plant built since 1970s. With a waste capacity of 420,000 tonnes/year the plant has a generating capacity of about 30 MW and is equipped to supply hot water to neighbouring residences. Others are under construction and planned[14].

3.3 Ash Residues

Solid residues from a mass burn facility basically consist of ash and residues from the air pollution control plant (Figure 3.2). A 'typical unit' operation that consumes a metric tonne of MSW will produce approximately:

- *150-300 kg of bottom ash* which comprises the heterogeneous material discharged from the burning grate of the combustor (grate ash) and the material that falls through the burning grate to be collected by hoppers below the furnace (grate riddlings). The ferrous metal is magnetically separated from the quenched bottom ash and sold for scrap.
- *10-30 kg of fly ash* which is the particulate matter removed from the flue gas stream prior to the APC system (electrostatic precipitator dust and cyclone dust). This fraction can also include the boiler ash which is particulate matter removed from the heat recovery systems i.e. boiler, economiser and superheater ash.
- *10-30 kg of air pollution control (APC) residue* which can comprise scrubber residue and/or bag house filter dust (APC residues are often combined with fly ash prior to disposal/utilisation).

Production quantities of solid residues from a FBC EfW plant are lower as non-combustible materials are generally separated from the waste feedstock prior to combustion (Figure 3.3). Information on typical input and outputs from an FBC plant was not available and complicated by the sand recycling loop. The main output streams from an fluidised bed incinerator are:-

- *boiler ash (or bottom ash)* which is ash removed from the fluidised bed and contains a high proportion of sand particles.
- *fly ash* which is the particulate matter removed from the flue gas stream prior to the APC system (cyclone dust).
- *APC residues* which can comprise scrubber residue and/or bag house filter dust (APC residues are often combined with fly ash prior to disposal/utilisation). The amounts of fly ash and APC residues generated in FBC EfW plants are highly dependent on the gas cleaning process and fuel composition.

Solid residues from the pyrolysis/melting EfW processes basically consist of molten slag (approximately 2 to 10% wt/wt of input) and APC residues, typically bag house filter dust (approximately 1 to 5% wt/wt of input).

The production quantities of solid residues from an EfW plant given above, are only approximate values and will vary depending on the waste feedstock characteristics and conditions of combustion. The total quantities of MSW produced in various countries, the amounts of MSW combusted in EfW treatment facilities and the generation rates of ash residues are shown in Figure 3.5 and summarised in Table 3.3 below.

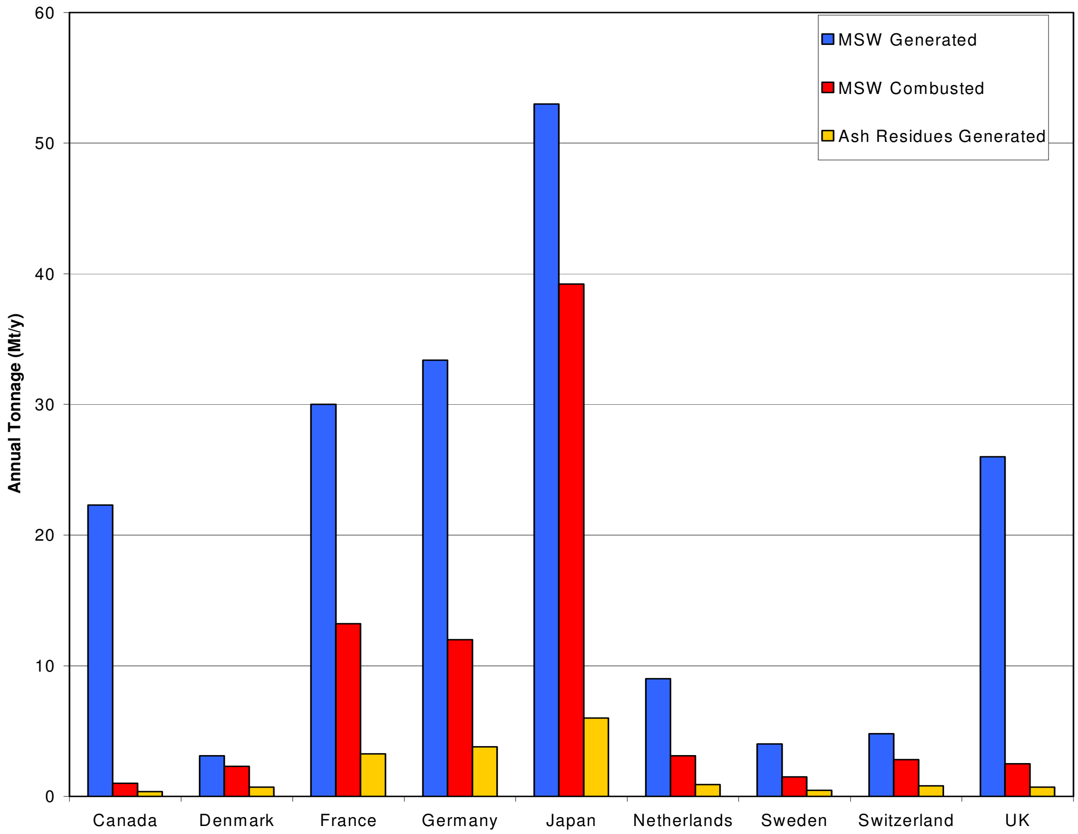


Figure 3.5 MSW Combustion and Ash Residue Generation

Country	MSW Generated (Mt/y)	MSW Combusted (Mt/y)	Ash Residues Generated (Mt/y)	Number of MSW Incinerators
Canada (1994)	22.3	1.0	0.35*	?
Denmark (1999)	3.2	2.3	0.7*	31
France (1999)	30	13.2	3.25	225
Germany (1999)	33.4	12.0	3.8	49
Japan (1995)	53	39.2	6.0	?
Netherlands (1999)	9	3.1	0.9*	10
Sweden (1998)	3.5	1.45	0.44	22
Switzerland (1999)	4.8	2.8	0.8*	30
UK (1999)	26	2.5	0.8*	31
USA (1994)	207	31	10.6*	114

- Estimated values

Table 3.3 MSW Generation and Production of Ash Residues (annual tonnages)[5, 6, 15, 16, 17, 18]

3.4 Co-Combustion

In many IEA/ISWA member countries, waste disposal is changing from being public controlled towards a free-market-economy. This will lead to more flexibility in terms of composition, collection and disposal, and it will create a demand for new and more flexible ways of utilising waste materials that meet the indispensable high environmental goals of modern society. Co-combustion of waste material together with coal could contribute to the disposal of large amounts of waste and it could avoid the construction of large and expensive EfW combustion plant, with additional advantage of a higher energy efficiency. A wide application of this technology also has the potential for making a significant environmental energy impact, through substituting large amounts of fossil fuel and thereby positively contributing to the reduction of primary energy consumption.

MSW is extremely variable in composition on both a seasonal and location basis and it is impractical to burn unprocessed MSW in combustion systems designed to burn coal[19]. Co-combustion trials using RDF and coal as the feedstock have been undertaken in a wide range of combustion technologies; these include circulating fluidised bed combustion (CFBC)[20], FBC[21], pulverised fuel fired plants[22], stoker-fired boilers[23] and cyclone fired combustors[24]. In Germany, analysis of ash residues produced from a 500 kW FBC co-firing RDF and coal led to the conclusion that bottom ash and fly ash can be disposed of as for coal ash residues or utilised in building material applications[25]. Although, the APC residues must be disposed of, they only represented around 2.5% of the mass combusted.

4 PHYSICAL AND CHEMICAL CHARACTERISTICS OF ASH RESIDUES

The physical and chemical characteristics of ash residues from waste combustion facilities vary considerably and are dependent on the original waste composition, front-end processing of the waste prior to combustion, and facility design and operation; including combustion temperature, air pollution control (APC) measures, etc. Knowledge of the waste ash residue characteristics is essential to determine appropriate management practices, utilisation opportunities and to ensure minimal environmental impact.

EfW facilities are dominated by mass burn plant and the main component of the solid residues is bottom ash, which represents about 30% by weight of the original waste and about 10% by volume. Bottom ash represents the residuals of combustion of MSW and is an inorganic, sterile material with the consistency of sandy gravel containing about 10 to 15% of ferrous metals. In mass burn facilities, after the ash is discharged from the grate, it is quenched in water before metals are separated by magnets for recycling. In FBC facilities, bottom ash is not quenched and contains a high proportion of sand particles from the fluidised sand bed.

Fly ash and APC residues arise from the particulate removal systems during cleaning of the flue gas and represent about 4% by weight of the input waste. They consist of fine particulates (that have been entrained in the gas stream) and gas cleaning reagents/products (such as lime or activated carbon and salts) removed from the flue gas stream. The main constituents of fly ash are carbon and metal oxides, and can also include substantial amount of organic pollutants that tend to form or attach themselves to the large surface area provided by the fine particles. Fly ash and APC residues can be conditioned with water to improve handling and pre-treated to reduce or immobilise potentially harmful constituents, such as heavy metals.

The range of characteristics of bottom ash, fly ash and APC residues from EfW facilities in the IEA/ISWA member countries are shown in Tables 4.1 to 4.7. The response from the plant operators regarding the chemical and physical properties of ash residues from their EfW facility was variable, ranging from full analyses, incomplete data to no data available.

4.1 Chemical Composition

Tables 4.1 and 4.2 show the range of major elements and general parameters for the bottom ash, APC and fly ash residues from EfW plants, whilst Tables 4.3 and 4.4 show variations in the concentrations of the minor elements, including trace organic compounds. The bottom ash represents the residuals from the combustion of waste, after the removal of the ferrous metal fraction. Figure 4.1 compares the major components in bottom ash and APC residues from a mass burn EfW facility in the UK.

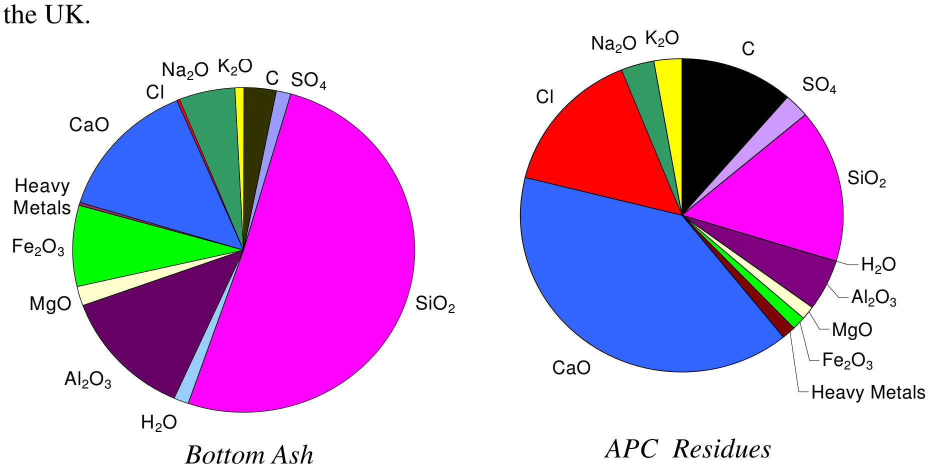


Figure 4.1 **Major Components in Bottom Ash and APC Residues**

Country	EfW Technology	pH	Total C	Total S	Si	Al	Mg	Fe	Ca	Na	K	Cl	F
			Concentration in % weight by weight										
Austria	**Mass Burn**	n.d.	1 - 2.5	1 -11	13 - 28	3 - 11	10 - 25	2 - 8	12 - 24	1 - 4.5	1 - 2.5	0.1 - 0.6	0.01 - 0.1
Belgium	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Canada	**Mass Burn**	11.2	n.d.	4.2	18	5	1	7	13	3	1	4	n.d.
Finland	**Mass Burn**	n.d.	12	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
France	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	46 - 69	0.5 - 3.5	4 - 8	5 - 12	0.8 - 11	0.2 - 1	0.02 - 0.6	0.01 - 0.08
Hungary	**Mass Burn**	11 – 11.9	n.d.	n.d.	n.d.	1.2 - 2	n.d.	0.7 – 1.5	8 - 12	0.45-0.8	0.5-0.8	n.d.	n.d.
Japan	**Mass Burn**	n.d.	0.5 - 2	<0.5	13 - 14	6 - 9	1 - 2	1 - 8	10 - 15	1 - 4	1 - 6	<1 - 11	<0.05 - 0.2
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	Pyrolysis/ melting[1]	n.d.	<0.01	0.04	20 - 39	8 - 16	2	3	16 - 36	3	0.5 - 1	0.02	n.d.
Nether-lands	**n.d.**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Norway	**Mass Burn**	9	2.5	n.d.	n.d.	3.5	0.8	7	8	1	0.6	n.d.	n.d.
Spain	**Mass Burn**	n.d.	n.d.	n.d.	8	8	1	12	13	1.5	<1	0.5	n.d.
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sweden	**Mass Burn**	11.9	n.d.	0.4	7 - 23	1 - 10	1	2 - 9	<1 - 10	<1 - 5	1 - 3	<0.1 - 0.3	<0.01
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
UK	**Mass Burn**	10.8 - 11.8	1.5 - 3	n.d.	<1 - 24	4 - 7	<1 - 12	6	7 - 10	<1 - 4	4 - 7	0.2 - 0.3	0.01
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. - No data available *[1] - Molten Slag*

Table 4.1 Characteristics of Bottom Ash Residues from EfW Plants; General Parameters and Major Elements

Country	EfW Technology	pH	Total C	Total S	Si	Al	Mg	Fe	Ca	Na	K	Cl	F
			Concentration in % weight by weight										
Austria	**Mass Burn**[2]	n.d.	<3	15-55	0.3 - 12	0.1 - 12	0.2 - 3	1 - 5	11 - 40	0.1 - 1.2	0.05 - 2.5	0.1 - 3	0.1 - 1.5
	Mass Burn[3]	n.d.	0.8 - 2.5	4.5 - 17	6.5 - 16	4 - 8	1 - 18	1 - 2	13 - 23	1.5 - 6.5	3 - 12	5 - 11.5	0.1 - 1.5
	FBC [2/3]	n.d.	n.d.	n.d.	n.d.	0.2/4	n.d.	1.7/11.7	n.d.	n.d.	n.d.	n.d.	n.d.
Belgium	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Canada	**Mass Burn**[2]	11.9	0.9	n.d.	n.d.	1	<1	<1	32	2	2.5	16.2	<0.01
Finland	**Mass Burn**[3]	n.d.	13	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
France	**Mass Burn**[2]	n.d.	<0.001 - 0.4	n.d.	6 - 12	2 - 7	1 - 1.3	1 - 1.5	20 - 35	2 - 3	2 - 5	3 - 14	n.d.
	Mass Burn[3]	n.d.	0.7 - 2	n.d.	7.5 - 14	5 - 10	1 - 3.5	0.02 - 0.4	8.5 - 18	2 - 10	2 - 13	7 - 14	n.d.
Hungary	**Mass Burn**[3]	12-12.8	n.d.	n.d.	n.d.	1.7-4.5	0.8-1.5	0.6-1.2	10-25	0.6-1.9	0.6-2.8	n.d.	n.d.
Japan	**Mass Burn**[3]	n.d.	1	1.2	6	1 - 3	1	1	25 - 38	3	3 - 8	18 - 19	n.d.
	FBC[2]	n.d.	n.d.	n.d.	n.d.	8	n.d.	3	15	2	3	9	<0.1
	Pyrolysis/ melting[2]	n.d.	<0.1	0.1	6	0.5	0.1	0.2	34	0.2	<0.1	30	n.d.
Nether-lands	**n.d.**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Norway	**Mass Burn**[3]	n.d.	n.d.	n.d.	6	8	1	2	>10	3	2.5	n.d.	n.d.
Spain	**Mass Burn**[3]	12.1	n.d.	n.d.	n.d.	2.5 - 4	1.5	1	30	2.5	2	20	n.d.
	FBC[2]	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sweden	**Mass Burn**[3]	n.d.	10	n.d.	10	3	2	1	1	1	6	1.4	0.05
	FBC[2]	n.d.	2	n.d.	n.d.	1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
UK	**Mass Burn**[2]	11.8	2 - 11	n.d.	7	3	<1	1	24 - 28	2	2	14 - 18	n.d.
	FBC[2]	n.d.	15 - 30	<1	19	8	1	3.5	18.5	1	1	<1	0.04

n.d. - No data available [2] *APC Residue samples* [3] *Fly Ash samples*

Table 4.2 Characteristics of APC/Fly Ash Residues from EfW Plants; General Parameters and Major Elements

Country	EfW Technology	Zn	Pb	Mn	Cr	Cd	As	Hg	Mo	Ni	PCDF	PCDD	TEQ	PCB	PAH
		Concentration in mg kg^{-1}									Concentration in ng g^{-1}				
Austria	**Mass Burn**	1500-5500	500-5500	300-1100	10-500	2-15	2-15	0.3-3	n.d.	50-700	0.01-0.2	0.01-0.2	0.001-0.008	<600	<100
Belgium	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Canada	**Mass Burn**	3,000	2,500	1,000	200	10	20	<2	50	300	0.03-0.12	0.05-0.14	<0.005	55-140	15-50
Finland	**Mass Burn**	n.d.	1,000	n.d.	n.d.	10	n.d.	0.1	n.d.	n.d.	0.07	0.07	0.005	n.d.	n.d.
France	**Mass Burn**	500-7,000	<20-4000	300-1100	150-850	<2-40	<1-30	<0.05-3	n.d.	60-250	n.d.	n.d.	0.004-0.04	n.d.	n.d.
Hungary	**Mass Burn**	2100-3000	1600-2600	400-600	25-40	6-14	n.d.	0.1-0.5	n.d.	n.d.	n.d.	n.d.	0.08-0.25	<2	2-5
Japan	**Mass Burn**	3,000-10,000	1,000-3,000	300-1,500	<1 - 500	1 - 100	1 - 30	<1 - 25	n.d.	150	0.02	0.08	n.d.	n.d.	n.d.
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	Pyrolysis/ melting[1]	250 - 4,000	30-500	4,000	400-1,000	3-500	0.1-5	<0.05	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Nether-lands	**n.d.**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Norway	**Mass Burn**	2,500	1,000	600	150	20	60	n.d.	10	150	n.d.	n.d.	n.d.	n.d.	n.d.
Spain	**Mass Burn**	1,500	500	700	30-250	<5	<1-4	0.03	n.d.	24-300	0.04	0.15	<0.001	n.d.	n.d.
	FBC	n.d.	1,500	n.d.	130	50	n.d.	20	n.d.	300	n.d.	n.d.	n.d.	n.d.	n.d.
Sweden	**Mass Burn**	300-7,000	100-3,000	300-1,000	30-80	2	<1-85	<1	<5	5-600	0.05	0.03	n.d.	n.d.	n.d.
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
UK	**Mass Burn**	1,500-3,000	500-2,500	650-850	100-250	2 - 10	5 - 7	<0.1 - 1	30	50 -300	0.09	0.49	<0.01	4	150
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

PCDF = Polychlorinated dibenzo furans *TEQ = Toxic equivalent (ratioed to 2,3,7,8-TCDD)* *PAH = Polyaromatic hydrocarbons* *n.d. - No data available*
PCDD = Polychlorinated dibenzo-p-dioxins *PCB = Polychlorinated biphenyls.* *[1] - Molten Slag*

Table 4.3 Characteristics of Bottom Ash Samples from EfW Plants; Minor Elements

Country	EfW Technology	Zn	Pb	Mn	Cr	Cd	As	Hg	Mo	Ni	PCDF	PCDD	TEQ	PCB	PAH
		Concentration in $mg\ kg^{-1}$									Concentration in $ng\ g^{-1}$				
Austria	**Mass Burn[2]**	500-2500	100-8000	100-800	20-300	10-1100	1-15	200-1600	n.d	20-400	2-20	3-16	0.1-1.5	<200	<50 - 700
	Mass Burn[3]	7000-25000	2500-7000	400-900	400-900	50-800	3-30	5-50	n.d.	50-700	2-30	5-80	1-4	<600	<100
	FBC[2/3]	1500/ 5300	650/ 1800	65/400	30/160	10/25	10/10	750/1	n.d.	45/85	130/3	70/0.3	3/0.03	0.02/<0.05	<0.2/<0.01
Belgium	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Canada	**Mass Burn[2]**	15,000	3,500	300	100	250	<800	15	<40	50	31	10	1	<150	12
Finland	**Mass Burn[3]**	n.d.	3,800	n.d.	n.d.	200	n.d.	1	n.d.	n.d.	510	510	20	n.d.	n.d.
France	**Mass Burn[2]**	2,000-37,000	1,500-10,000	n.d.	20-80	100-600	16-17	10-80	n.d.	40-90	n.d.	n.d.	n.d.	n.d.	n.d.
	Mass Burn[3]	900-67,000	3,000-13,000	100-700	100-650	100-500	10-50	5-80	n.d.	20-200	n.d.	n.d.	0.001-0.004	n.d.	n.d.
Hungary	**Mass Burn[3]**	1400-6600	130-3000	240-450	20-60	10-200	0.5-45	0.1-3.5	0.1-4.5	6-20	n.d.	n.d.	1-1.8	n.d.	n.d.
Japan	**Mass Burn[3]**	10,000	1,000-9,000	200-900	70-800	100	1-10	4-10	n.d.	40	<1-20	<1-30	1	11	125
	FBC	4,000	1,500	1,000	<1	25	10	1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	Pyrolysis/ melting	<100	1	n.d.	7	1	1	3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Nether-lands	**n.d.**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Norway	**Mass Burn[3]**	40,000	6,000	1,800	1,500	400	50	3	30	140	n.d.	n.d.	n.d.	n.d.	n.d.
Spain	**Mass Burn[3]**	5-11,000	2,000-5,000	250-600	100-150	50-200	<2-25	3-8	n.d.	20-70	9	13	0.3	n.d.	n.d.
	FBC	n.d.	1,400	n.d.	280	15	n.d.	20	n.d.	170	n.d.	n.d.	n.d.	n.d.	n.d.
Sweden	**Mass Burn[2,3]**	6,000-9,000	800-2,000	2,000	100-200	10-200	40-360	0.5-30	10	30-150	8	9	n.d.	n.d.	0.2
	FBC	6,000	800	n.d.	n.d.	20	n.d.	1	n.d.	150	n.d.	n.d.	n.d.	n.d.	n.d.
UK	**Mass Burn[2]**	6,000-16,000	2,000-4,500	400-1,000	60-140	100-260	10-130	10-20	10-50	20-140	1.35	0.3	1.65	6	60
	FBC	500	400	400	100	5	30	7	10	90	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. - No data available
PCDF = Polychlorinated dibenzo furans
PCDD = Polychlorinated dibenzo-p-dioxins
TEQ = Toxic equivalent (ratioed to 2,3,7,8-TCDD)
PCB = Polychlorinated biphenyls.
PAH = Polyaromatic hydrocarbons
[2] APC Residue samples
[3] Fly Ash samples

Table 4.4 Characteristics of APC/Fly Ash Residues from EfW Plants; Minor Elements

Country	EfW Technology	Na	K	Ca	Mg	SO_4 (as SO_3)	Cl	NH_3	NO_3 (as N)	NO_2 (as N)	DOC	Fe	Mn	Ni	Mo	Cd	Cr	Cu	Pb	Zn	Hg
		Leached Concentration, mg kg^{-1}																			
Austria	Mass Burn*	n.d.	n.d.	1700	<10	100-1600	2000	10	<3	0.5-5	250	0.5	<0.5	<0.5	n.d.	0.1	<0.5	2.5-5	20-60	1.5	<0.01
Belgium	Mass Burn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Canada	Mass Burn	80	n.d.	35	n.d.	1030	n.d.	n.d.	n.d.	n.d.	n.d.	16	10	0.5	<0.1	0.1	<0.1	1	0.6	47	<0.1
Finland	Mass Burn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
France	Mass Burn	n.d.	n.d.	n.d.	n.d.	400-8,700	350-9,200	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.5-2	n.d.	<0.9	<0.1-1	0.4-40	<2-95	<1-5.5	<.005-0.2
Hungary	Mass Burn	80-250	90-360	1800-4300	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.05	<0.2	n.d.	n.d.	<0.02	0.1-0.5	0.3-0.7	<0.006	0.005-0.3	<0.002
Japan	Mass Burn	120	60	430	n.d.	10	240	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.1	<0.1	1	0.3	0.3	<0.1
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	Pyrolysis/ melting[1]	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.1	n.d.	n.d.	<0.1	n.d.	<0.1
Nether-lands	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.1	n.d.	n.d.	<0.1	n.d.	<0.1
Norway	Mass Burn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Spain	Mass Burn	n.d.	n.d.	n.d.	n.d.	n.d.	2,500	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.6	n.d.	n.d.	0.6	11.5	0.7	7	n.d.
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sweden	Mass Burn	n.d.	n.d.	39,000	n.d	13,000	6,000 - 84,000	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	40	n.d.	0.1 - 1	0.2 - 3.5	2 - 810	290 - 440	30 - 1960	<0.1
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
UK	Mass Burn	160 - 925	60-690	230 - 2220	<0.1 -0.9	100 - 240	220 - 1320	8	<1	<0.2	230	<0.1 - 1	<0.1	<0.1	<0.1 - 0.2	<0.1	<0.5	2 - 5	0.1 - 3.5	<0.1 - 1	<0.1
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. - No data available
** Granular Leached Concentrations*

[1] - Molten Slag
DOC – Dissolved Organic Carbon

Table 4.5 Characteristics of Bottom Ash Residues from EfW Plants; Maximum Concentration Available for Leaching

Country	EfW Technology	Na	K	Ca	Mg	SO_4 (as SO_3)	Cl	NH_3	NO_3 (as N)	NO_2 (as N)	DOC	Fe	Mn	Ni	Mo	Cd	Cr	Cu	Pb	Zn	Hg
		Leached Concentration, mg kg^{-1}																			
Austria	**Mass Burn[2/3] ***	n.d.	n.d.	15000/ 1700	500/ <10	25000/ 25000	30000/ 100000	10/5	10/<3	1/0.5	50/20	<1.5/ 0.5	<1.5/ <0.5	<1.5/ <0.5	n.d.	0.05/ 0.1	<1.5/ <0.5	<1.5/0 .5	0.1/ 200	1/10	<0.01/<0. 01
	FBC[2/3] *	n.d.	n.d.	n.d.	n.d.	16,000 /30500	400/ 15000	n.d.	<20/ <20	3.5/ 0.5	n.d.	0.2/ 0.1	0.2/ 0.1	<1/ <1	n.d.	<0.1/ <0.1	0.1/ 1.8	0.1/ 0.1	0.7/6	0.5/2	0.08/ 0.01
Belgium	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Canada	**Mass Burn[2]**	900	1000	6000	0.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.5	0.4	<0.1	<0.1	<0.1	<0.1	0.2	50	5	<0.1
Finland	**Mass Burn[3]**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
France	**Mass Burn[2]**	n.d.	n.d.	n.d.	n.d.	0.6-1.3	8- 27	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3-5	n.d.	0.3- 1.7	2-8	6	430- 2,655	60- 130	0.03- 1
Hungary	**Mass Burn[3]**	1000- 1600	2000- 2800	2500- 4400	1-25	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.1	0.002	<0.02	0.01	0.001 -0.3	0.1- 1.2	0.01- 0.25	<0.25	0.1- 1.2	0.01-0.02
Japan	**Mass Burn[3]**	n.d.	n.d.	n.d.	n.d.	n.d.	1.8	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.1	<0.1	n.d.	<36	n.d.	<0.1
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	Pyrolysis/ melting	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.1	n.d.	n.d.	<0.1	n.d.	<0.1
Nether- lands	**n.d.**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Norway	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Spain	**Mass Burn[3]**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1,200	400	n.d.	n.d.	1,500	1,800	19,000	41,000	40
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sweden	**Mass Burn[4]**	n.d.	n.d.	38,000/ 330,300	n.d.	n.d.	84,000/ 71,500	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.2/ <0.1	0.24/ <0.1	2/ <0.1	440/ <0.1	32/ <0.1	<0.1/ <0.1
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
UK	**Mass Burn[2]**	1,200	1,650	0.15	6,900	720	14,100	3.2	4.5	n.d.	n.d.	<0.1	<0.1	<0.1	0.26	<0.1	0.1	0.3	59	5	<0.1
	FBC[2]	n.d.	n.d.	n.d.	n.d.	2	800	n.d.	<0.1	<0.2	n.d.	<0.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. - No data available
** Granular Leached Concentrations*
[2] APC Residue samples
[3] Fly Ash samples
[4] Fly Ash + APC residue samples untreated / Fly Ash + APC residue samples treated
DOC – Dissolved Organic Carbon

Table 4.6 Characteristics of APC/Fly Ash Residues from EfW Plants; Maximum Concentration Available for Leaching

Country	EfW Technology	Bulk Density kgm^{-3}	Quartz	Feldspar	Lime	Particle Size Distribution, % passing sieve									
			% weight by weight (dry basis)			-25 mm	-12.5 mm	-9.5 mm	-4.75 mm	-2.4 mm	-1.2 mm	-600 µm	-300 µm	-150 µm	-75 µm
Austria	**Mass Burn**	800-1200	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Belgium	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Canada	**Mass Burn**	1,600	47	n.d.	12.5	93	73	62	40	29	19	14	9	6	4.5
Finland	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
France	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Hungary	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Japan	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	Pyrolysis/ melting[1]	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Nether-lands	**n.d.**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Norway	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Spain	**Mass Burn**	2,000	40	n.d.	18	n.d.	n.d.	35	20	19	6.5	4	n.d.	2.5	n.d.
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sweden	**Mass Burn**	1,030	50	10	13.5	100	95	85	70	55	40	25	16	7	5
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
UK	**Mass Burn**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	FBC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. - No data available *[1] - Molten Slag*

Table 4.7 Characteristics of Bottom Ash Residues from EfW Plants; Physical and Mineralogical Properties

The leaching behaviour of the ash residues is shown in Tables 4.5 and 4.6. A number of leaching tests have been designed and used as a basis for establishing ash management requirements or to determine the suitability of ash management practices with regard to ash residue streams[26]. It has been found that the release of elements during regulatory leach tests is primarily solubility controlled, with release influenced by changes in ash alkalinity when the extraction final pH is not specified[1]. Leaching behaviour is fundamentally dynamic in nature and can change over time. The general consensus has been that in order to fully characterise the dynamics of leaching behaviour, more than one type of leach test is needed, at a minimum, including those tests which can give knowledge of total availability for leaching, elemental solubility as a function of pH and the effect of increased liquid/solids ratio or time on cumulative release[26,27]. From the EfW operators point of view, the preference is for as few tests as possible and their response indicates only one type of leaching test is generally employed. For the majority of countries, the method used appeared to be based on the maximum availability test with pH control[27]. In countries such as the UK, the less aggressive granular leaching test was adopted[28].

Tables 4.1 to 4.7 illustrate that different fuel sources and combustion processes generate residues with significantly different characteristics. The majority of waste treated in mass burn EfW plants was MSW. Smaller amounts of RDF, light commercial waste and clinical waste were also utilised but these tended to be in addition to the MSW waste and the data given for the ash residues did not distinguish the feedstock type. Although comparisons between waste sources and ash residue characteristics is limited, the data supplied demonstrates the following principal differences between the residues:

- Inorganic salts were present in all the waste ash residues. The major components being Si, Al, Ca and Fe.

- Many inorganic salts were found to be highly soluble in aqueous media. These include cations such as Na, K, Mg and anions of Cl and SO_4.

- The APC residues samples from mass burn, FBC and pyrolysis/melting EfW facilities contained high levels of Ca (1 to 40%) and Cl (9 to 30%) relative to the bottom ash samples, which reflects the lime added for acid gas abatement. High levels of Ca and Cl were also reported in the fly ash samples from Japan and Spain.

- In general, levels of soluble Na and K appeared to be higher in the APC residues relative to the bottom ash in mass burn waste combustors.

- Heavy metals were present in all waste ash residue streams and their concentrations varied significantly with waste source and combustion conditions. For example, levels of Cd in the bottom ash from mass burn plants ranged from 1 to 100 mg kg^{-1}; Pb 100 to 5,500 mg kg^{-1}; As <1 to 85 mg kg^{-1}; and Hg <0.02 to 400 mg kg^{-1}.

- Fly ash and APC residues from mass burn plants contained higher levels of the more volatile and potentially harmful constituents (10 to 1,100 mg kg^{-1} Cd; 100 to 13,000 mg kg^{-1} Pb; <1 to 800 mg kg^{-1} As; and 0.1 to 1,600 mg kg^{-1} Hg) relative to the bottom ashes. This compared with 5 to 25 mg kg^{-1} Cd; 400 to 1,800 mg kg^{-1} Pb; 10 to 30 mg kg^{-1} As; and 1 to 750 mg kg^{-1} Hg in APC residues from FBC plants.

- The metals in the bottom ash fraction are generally considered to be less mobile and compared to the fly ash and APC residues contained significantly lower concentrations of potentially leachable fractions of these metals. This was particularly evident for one EfW facility in Spain were leachable concentrations of Pb from fly ash residues was 19,000 mg kg^{-1} and Zn was 41,000 mg kg^{-1}.

- Trace organics of potential human health concern have been quantified in MSW bottom ash from mass burn plants. These include the polychlorinated dibenzo furans (PCDFs) and the polychlorinated dibenzo-*p*-dioxins (PCDDs). The data presented in Table 4.3 (and reported literature[15]) indicates that most EfW facilities are able to achieve total PCDF and PCDD levels for bottom ash of below 0.5 ng g^{-1}.

- Both PCDFs and PCDDs are absorbed or formed *in situ* on fine particles during combustion. Consequently, levels of both these groups of compounds were significantly higher in the APC and fly ash residues (0.3 to 510 ng g^{-1}). This was reflected in the elevated TEQ (Toxic Equivalent) levels for the APC and fly ash residues in comparison to the bottom ashes. This is a toxicity index, summing the equivalent toxicity of the individual isomers as the most toxic of the dioxins - 2,3,7,8-TCDD.

- PCDDs and PCDFs are generally considered to be strongly absorbed or otherwise associated with solid surfaces of ash residue and therefore to be highly insoluble in aqueous environments, e.g. rainwater. Therefore it is considered unlikely that they will leach to a significant extent from a landfill and contaminate ground water. Concentrations of PCDDs and PCDFs in leachate collected from ash residues monofills have characteristically been reported to range from non-detectable to parts per quadrillion (ppq) levels, i.e. at levels that are presently considered to be below regulatory concern[11].

- Another group of toxic compounds are the condensed polyaromatic hydrocarbons (PAHs). PAHs are a measure of the quality of the combustion process. Well operated EfW combustors can easily produce bottom ash with a total PAH concentration of less than 100 ng g^{-1}. PAH levels for the bottom ashes, fly ashes and APC residues reported in Tables 4.3 and 4.4 ranged from <0.01 to 700 ng g^{-1}.

- Polychlorinated biphenyls (PCBs) are potential precursors for PCDDs and PCDFs and are also found in MSW ash residues. Low levels of less than 10 ng g^{-1} are reported to be achievable. The higher values reported in Table 4.3 may be caused by the inclusion of boiler ash in the bottom ash process stream.

4.2 Physical and Mineralogical Properties

The physical and mineralogical properties of the bottom ash residues from mass burn plants in Canada, Spain and Sweden are reported in Table 4.7. No data on physical and mineralogical properties was available for FBC plants and reported data on APC and fly ash residues from mass burn plants was negligible. Although the data available is limited the following observations were made regarding the bottom ash residues:

- The most abundant crystalline mineral present in the bottom ashes was quartz (40 to 50% wt/wt), with small amounts of lime (12.5 to 18%) and feldspar (10%).

- The concentration of fine material in bottom ash is an important consideration when bottom ash is to be used as an aggregate substitute. The percentage fines can frequently create problems because that fraction is highly absorptive for water, asphaltic cement and Portland cement. Frequently, high fine contents create a material that has a tendency towards freeze-thaw susceptibility and durability failure. The percentage fines (i.e. fraction passing through a 75 µm sieve) was low (less than 5%) for the three bottom ash samples from mass burn EfW facilities reported in Table 4.7.

4.3 Summary of Ash Residue Characteristics

Knowledge of physical and chemical properties of ash residues is essential in order to determine appropriate management practices, utilisation opportunities and to ensure minimal environmental impact. However, as shown above, the physical and chemical characteristics of EfW combustion residues vary widely. The properties of ash residues are affected by factors such as: the original waste composition, front-end processing of the waste prior to combustion, and facility design and operation; including combustion temperature, air pollution control (APC) measures, etc.

The bottom ash, from mass burn EfW, plant represent the residuals from the combustion of MSW, after the removal of the ferrous metal fraction. In FBC facilities, bottom ash contains a high proportion of sand particles from the fluidising sand bed. Fly ash and APC residues consist of fine particles that have been entrained in the gas stream. APC residues also contain the gas cleaning reagents, such as lime, and their products.

The main components in all waste ash residue streams were the inorganic salts of Si, Al, Ca and Fe. These, together with cations and anions Na, K, Mg, Cl and SO_4, were shown to be highly soluble in aqueous media and if not properly managed can report to the environment and have the potential to degrade groundwater. At ash residue disposal sites, careful consideration of appropriate measures to mitigate or manage the report of inorganic salts to the environment is required.

Metals were shown to be present in all ash residue fractions, and the EfW operation can have a pronounced impact upon metal speciation and the report of metal species to various ash residue fractions. Various legislative and regulatory instruments and activities have addressed or sought to address (e.g. control and/or mitigate) the presence of heavy metals in ash residues, for example: antimony, arsenic, cadmium, chromium, copper, lead, mercury, nickel, tin and zinc. Compared to other ash residue fractions, fly ash and APC residues characteristically contain significantly higher concentrations (though not always the largest total amounts) of potentially leachable fractions of these metals. Metals in bottom ash streams are generally considered to be less mobile.

Trace organics of potential human health concern have been quantified in MSW bottom ash from mass burn plants. These include the polychlorinated dibenzo furans (PCDFs), the polychlorinated dibenzo-*p*-dioxins (PCDDs), polyaromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs). The data presented and reported in literature indicates that most well operated MSW EfW facilities are able to achieve low levels of these compounds in bottom ash streams. Fly ash and APC residues can contain higher levels of PCDDs and PCDFs.

5 RESIDUE CATEGORISATION

5.1 Legislative Background

In European and Western countries, residues from EfW plants are currently classified as either special or non-special wastes. The Special Waste Regulations 1996 (SWR 96) implement European Council Directive 91/689/EEC on Hazardous Waste and broadly define special waste as those wastes containing certain listed substances and, by the presence of the substances being:-

- hazardous to human health or;
- present a risk to the environment or;
- medicinal products available only on prescription or;
- having a flash point of 21^{o}C or less.

A precise definition of hazardous waste is provided both in the directive and by a list of hazardous waste, which has been drawn up (European Council Decision 94/904/EC)[29]. This list of hazardous wastes is broad, embracing waste both with and without hazardous properties. Wastes filling the description may generally have hazardous properties, but the levels of particular constituents in an individual case can result in the waste having no such properties. An approach for assessing whether a waste is special, under the SWR 96, is set out in the Environment Agencies Special Waste Guidance Note[29].

Since the Hazardous Waste directive (91/689/EC) was adopted, Member States have submitted proposals to the Commission for additional types of waste to be included on the list, one of which is combustion residues. Inclusion could qualify these wastes as 'hazardous waste' if they displayed certain hazardous properties. This would mean that they would be subject to Special Waste Regulations and would also be subject to stricter transfrontier shipment controls.

5.2 Residue Classification

5.2.1 Bottom ash

In the majority of IEA/ISWA member countries, bottom ash from mass burn MSW facilities is classified as non-special waste (Table 5.1). The assessment of the hazardous nature of the waste residue is based mainly on their chemical characteristics; i.e. whether the waste exceeds the threshold concentration values for specified components. The threshold concentration values vary nationally and are typically based on the chemical components of the residue and/or water leached concentrations of constituents, such as Cd, Cr, Cu, Pb, Zn, Hg and Ni. In most countries, waste residues classified in the non-special waste category benefit from lower landfill tax costs. In Austria and Hungary, bottom ash from mass burn MSW facilities is classified as special waste and subsequently incurs higher landfill costs (Section 9).

5.2.2 APC residues

In the majority of IEA/ISWA member countries, the principal concerns for APC residues are the presence of higher levels of heavy metal and organic compounds and the high level of hydrated lime (calcium hydroxide) which originates from the gas cleaning systems. Threshold values for categorisation of the waste residues are usually exceeded and APC residues are generally classified as special waste (Table 5.1). The only exception to this in the current study, was a CFBC plant in the UK co-combusting coal and waste with a low sulphur content. Limestone requirement for sulphur abatement (in-bed) is minimised and levels of calcium oxide in the bag filter ash residues is low thus avoiding special waste categorisation.

Country	EfW Technology	Residue Type	Residue Categorisation: Not Special Waste	Residue Categorisation: Special Waste	Regulatory Constraint	Directive
Austria	**Mass Burn**	Bottom Ash		√	Chemical composition and water leached concentrations	Austrian landfill regulation
		Fly Ash & APC		√	Chemical composition and water leached concentrations	Austrian landfill regulation
	FBC	Fly Ash & APC	n.d.	n.d.	n.d.	n.d.
Belgium	**Mass Burn**	Bottom Ash	√		n.d.	Belgium Directive; Vlarem II; Landfill Class I
		Fly Ash & APC		√	n.d.	Belgium Directive; Vlarem II; Landfill Class II
Canada	**Mass Burn**	Bottom Ash	√		Continued analysis of leachability; Removal of ferrous metals; Record keeping on uses (impervious cover - asphalt); and Placement above water table.	B.C. Ministry of Environment, Lands & Parks/B.C. Waste Management Act.
		APC		√	Storage in temporary special waste monofill cell, Will be delisted as a special waste once in-situ stabilisation deemed to have taken place.	B.C. Ministry of Environment, Lands & Parks/B.C. Waste Management Act.
		Treated APC	√		Must pass monthly leachability test; To be disposed in regular MSW landfill or beneficially reused	B.C. Ministry of Environment, Lands & Parks/B.C. Waste Management Act.
Finland	**Mass Burn**	APC		√	n.d.	n.d.
France	**Mass Burn**	Bottom Ash	√		Department Order of 9/9/97 re landfilling of municipal waste	n.d.
		Fly Ash & APC		√	Waste must be treated prior to being admitted to landfill. Wastes are considered as treated if they satisfy leaching test (XPX 31-210)	n.d.
Hungary	**Mass Burn**	Bottom Ash		√	Hazardous waste Class III. in Hung. Regulation: Landfill must have 3 x 20 cm mineral liners, a single HDPE liner (min. 2.5 mm) and geomembrane	Order of Hungarian Government 102/1996 (VII.12.)
		Fly Ash		√		
Japan	**Mass Burn**	Bottom Ash	√		Must satisfy leachability test (mg/l): Cd <0.3; Pb <0.3; Cr <1.5; As <0.3; Hg <0.005; Se <0.3	Environment Agency Notice No.13 'Target value of landfill'.
		Fly Ash & APC		√	Cannot be landfilled or dumped in the sea without treatment. After treatment must satisfy leachability test (mg/l): Cd <0.3; Pb <0.3; Cr <1.5; As <0.3; Hg <0.005; Se <0.3	Environment Agency Notice No.13 'Target value of landfill'.
	FBC	All Residues	n.d.	n.d.	n.d.	n.d.
	Pyrolysis/ melting[1]	All Residues	n.d.	n.d.	Must satisfy leachability test (mg/l): Cd <0.3; Pb <0.3; Cr <1.5; As <0.3; Hg <0.005; Se <0.3	Environment Agency Notice No.13 'Target value of landfill'.
Nether-lands	**n.d.**	Bottom Ash	√		Physical & chemical characteristics + leached concentrations	Dutch regulation (IPO/VROM)
		Fly Ash		√	Cannot be landfilled without treatment	
Norway	**Mass Burn**	Bottom Ash	√		TOC<3%, no other limits	No specific regulations. Local authority regulations.
		Fly Ash & APC		√	Has to be treated before landfilling.	National Authorities
Spain	**Mass Burn**	B A+Treated FA	√		n.d.	Spanish Landfill Directive
		Fly Ash & APC		√	Residues must be stabilised (mixed with lime and cement) prior to landfill	Spanish Landfill Directive
	FBC	Fly Ash & APC		√	Landfills must provide containment equivalent to 5m of soil with a permeability no greater than 10^{-9} m/seg	Spanish Landfill Directive
Sweden	**Mass Burn**	Bottom Ash[1] and Treated APC	√		Concessions from the individual landfill operators. Separation of magnetic and 'untreated' material. The remainder is used to cover the landfill	Swedish Landfill Directive
		Fly Ash & APC		√	Concessions from the individual landfills. Solidification or humidification and mixing with ash from coal combustion.	Swedish Landfill Directive
	FBC	Fly Ash & APC		√	n.d.	n.d.
UK	**Mass Burn**	Bottom Ash	√		Licensed landfill site; Permeability no greater than 1×10^{-9} ms^{-1}; Handled as a contaminated soil; Must be deposited in lined pits, effluent produced to be removed.	UK Landfill Directive
		Fly Ash & APC		√	Containment landfills with permeability no greater than 1×10^{-9} ms`1; Consignment note and damping down of residue prior to landfilling in a mono disposal site required.	UK Landfill Directive
	FBC	Fly Ash & APC	√		Controlled waste; CaO<10%	UK Waste Directive

[1] Bottom ash from combustor burning clinical waste also categorised as Special Waste. Residues landfilled on separate area in landfill site (not co-disposal with other waste) *n.d. - no details given*

Table 5.1 Waste Combustion Residue Categorisation and Disposal Regulations

APC residues can be treated to stabilise leachable components and thus avoid the special waste categorisation. This is proving to be a viable option in countries where disposal costs for special waste are high.

5.2.3 Fly ash

Fly ash from MSW EfW plants, generally contain lower levels of calcium hydroxide than found in APC residues. However, the current practice of mixing fly ash with APC residues prior to disposal in many IEA/ISWA member countries, incurs the special waste categorisation on the mixed residue (Table 5.1) and, subsequently, higher landfill costs.

6 CURRENT RESIDUE TREATMENT PRACTICES

A range of treatment and pre-treatment processes were identified in this study for both disposal, recovery and re-use operations. These treatment techniques include crushing, weathering, separation processes, mixing, chemical processes, thermal processes and solidification/stabilisation of the ash residues and are primarily carried out in order to reduce the potential for environmental impacts that may result from disposal or utilisation practices. The various treatment process are outlined below, whilst their key features, advantages and limitations are summarised in Table 6.1. The treatment processes for disposal operations, recovery and re-use operations reported by the EfW plant operators who responded to this study are shown in Tables 6.2 and 6.3.

6.1 Crushing

Crushing is a general pre-treatment technique for re-use applications, which is undertaken to refine the particle size distribution of the residues, making the material more usable in construction materials such a cement and concrete. This procedure is commonly undertaken in conjunction with scrubbing (see below in Section 6.2), where the residue, usually the bottom ash, is washed with a leachant to remove some of the heavy metal components.

6.2 Weathering

Weathering or ageing is carried out by temporarily storing the residue in stockpiles before removal from site. Because of the chemical instability of the residue leaving the combustion process, exposure to the atmosphere can result in significant stabilisation reactions occurring. The principal reactions are brought about by hydration and carbonisation. The time required to stabilise the ash residues depends upon the stockpile conditions and ash composition. Periods of three to six months are often necessary before weathering reactions produce significant changes in the residue characteristics[30]. Scrubbing the ash residues, to remove some of the heavy metal components, is essentially an accelerated weathering technique. The efficiency of the scrubbing or weathering process to remove heavy metals is highly dependent of the characteristics of the ash stream. For example, APC ash with a high lime content will have a high pH and the levels of leached heavy metals will be significantly reduced[26]. Tables 6.2 and 6.3 indicate that for IEA Member countries weathering or ageing is a general pre-treatment technique for re-use applications as opposed to disposal requirements for landfilling.

6.3 Separation

Separation may be undertaken to improve the properties or behaviour of ash residue for utilisation applications, to remove harmful constituents prior to further treatment, utilisation or disposal, to conform to regulatory requirements, and to reduce the volume of ash. Separation or screening processes are well established techniques in the majority of IEA Member countries (Table 6.3), often incorporated into the process design of facility. There are three basic elements to the separation process (i) removal of ferrous material; (ii) removal of non-ferrous metals; and (iii) the separation of over-sized particles. It is common practice in the majority of IEA Member countries to magnetically remove ferrous material contained within the bottom ash for recycling purposes. Less attention is paid to the removal of other non-ferrous metals, such as aluminium. Screening of the bottom ash to remove the large components is often carried out to give the residue a particle size distribution that is more suitable for re-use, particularly in construction industry applications.

6.4 Mixing

The mixing of APC residues with bottom ashes is commonly applied as a strategy to produce a waste residue stream capable of meeting landfill acceptance criteria. The toxicity of the residue, however, is not reduced only diluted within a larger volume. Combined residues require more sophisticated treatment if

Treatment	Key Features	Advantages	Limitations
Crushing		• Simple physical operation. • The toxicity of the residue is reduced. • Number of potential uses for treated residue. • Relatively inexpensive.	• Secondary effluents are produced which need to be treated and/ or disposed of.
Weathering	• Bottom ash is temporarily stockpiled (weeks/months) and exposed to the environment allowing the bottom ash to age and stabilise, through concentration and oxidation reactions. The ash is often screened before it is stockpiled.	• Stabilisation and leaching occur before use. • Stockpiling allows the ash to be stored in reserve to meet seasonal demands. • Simple technique, that does not require complicated processes. • Relatively inexpensive.	• Considerable space is required to store the ash during weathering • Secondary effluents are produced which need to be safely collected and treated. • Process depends upon stockpile and weathering environments, which cannot be totally controlled. The time required for the ash to stabilise will therefore vary.
Separation	• Removal of ferrous material. • Removal of non-ferrous metals. • Separation of over-sized particles.	• Simple physical operation often undertaken at combustion plant. • Established technique. • Recycling and re-use of some materials possible. • Volume of ash is reduced. • Relatively inexpensive.	• The heavy metal load the ash is not significantly reduced, therefore further treatment may be required before it can be utilised. • Dust is generated during screening process.
Mixing	• Bottom ash mixed with fly ash prior to re-use or disposal .	• Established method which is particularly appropriate to enable the disposal of fly ash to landfill. • Simple physical operation. • Relatively inexpensive.	• Combined residues require more sophisticated treatment if it is to be further used. • The toxicity of the residue is not reduced only diluted within a larger volume. • Mixing is more of a disposal option rather than a treatment technique.
Chemical Processes	• Combination of the residue with soluble phosphate and lime.	• Reduction in the toxicity of the residue is achieved. • The treated residue could potentially have a number of uses, particularly in the construction industry. • The volume of the residue is only slightly increased after treatment.	• Complex technique. • Only applicable for treating lead and cadmium within the residue some secondary effluents may be produced which add to the disposal problem.
Thermal Processes	• Vitrification is achieved by melting the material with additives to form an homogenous glass phase, which immobilises heavy metals and other substances.	• After vitrification the leachability of the residue is substantially reduced and the material is highly resistant to aqueous, chemical and thermal attack. • Vitrification can be applied to fly ashes with a variety in composition, including those with a high variability in the concentration of heavy metals. • Large reduction in residue volume. • Low dust generation. • Established technique. • Number of uses for end product. • Glass forming additives are inexpensive.	• Gaseous emissions(e.g. Cl, SO_2, Hg etc)and other volatiles previously trapped in the residue. • Secondary treatment of gaseous emissions is required before release to the atmosphere. • High energy requirements to heat the residue, therefore the technique can be expensive. • Complex technique, requiring specialist equipment and trained personnel.
Solidification/ Stabilisation	• Immobilisation of contaminants through the addition of cementious, pozzolanic materials or additives.	• Some cementious/pozzolanic materials such as cement kiln dust or coal fly ash are waste products of other industries. • Simple established technology. • Low capital and running costs. • Significant reduction the environmental impact of the residue can be achieved, provided that severe alkaline conditions do not predominate. • Can be applied to MSW residues that have variations in their content. • Strength and durability of end product can be controlled to a certain extent. • Improved handling properties of the residue after treatment (minimising dust).	• The weight and sometimes volume of the residue is increased. • Setting and curing can be delayed or prevented by the presence of some organic material and other compounds. • Leaching can take place under extremes of acidic/ alkaline conditions. • Properties of the end product are influenced by the variability of the ash residue.

Table 6.1 The Advantages and Limitations of Residue Treatment Techniques

Country	EfW Technology	Residue Type	Treatment	Description
Austria	Mass Burn	Bottom + Fly Ash	Solidification	Mixing and removal of ferrous scrap; solidification with cement/water.
Belgium	Mass Burn	Fly Ash + APC	Solidification	n.d.
Canada	Mass Burn	APC	Stabilise	Stabilise leachable metals with phosphoric acid.
Finland	Mass Burn	Fly Ash + APC	Solidification	Solidification in concrete.
France	Mass Burn	Fly Ash + APC	Solidification	Solidification in concrete.
Hungary	Mass Burn	Fly Ash	Solidification	Stabilisation with cement and other additives prior to deposition in a monofill beside MSW landfill site.
Japan	Mass Burn	Fly Ash	Solidification,/ stabilisation	Stabilised (chelate or solvent); solidification by adding concrete or by melting.
	FBC	Fly Ash	None	Landfilled without treatment.
Nether-lands	Mass Burn	Fly Ash/APC	Solidification, washing, melting.	See Dutch experience in Section 6.8.
Norway	Mass Burn	Fly Ash + APC	Solidification, stabilisation	Acid leaching, solidification/ stabilisation.
Spain	Mass Burn	Fly Ash + APC	Solidification, stabilisation	Solidification, stabilisation or bagged and deposited in boxes.
	FBC	Fly Ash	None	Landfilled without treatment.
Sweden	Mass Burn	Fly Ash + APC	Solidification, stabilisation	Solidification with cement and stabilisation (Bamberg principle) and in certain cases landfilling in 'waterhydraulic' cell. Note: in certain districts landfilled without treatment.
	FBC	APC	Moistening/ compacting	Moistening, compacting in landfill.
UK	Mass Burn	Fly Ash + APC	Dry Bagged	Primary containment in polythene inner bags and polypropylene outer bag which is landfilled.
	Mass Burn	APC	Dampened	Dampened with water through high speed mixers at landfill site.
	FBC	APC	Dry, acid neutralisation	Maintained dry, H_2S scrubber, acid neutralisation.

APC = Air Pollution Control Residues *FBC = Fluidised Bed Combustion*

Table 6.2 Treatment Processes for Disposal Operations

Country	EfW Technology	Residue Type	Treatment	Recovery/Re-Use Description
Austria,	Mass Burn	Bottom Ash	Magnetic separation.	Iron recovery.
Canada	Mass Burn	Bottom Ash	Magnetic separation.	Iron recovery, landfill intermediate cover & road sub-base.
France	Mass Burn	Bottom Ash	Ageing, magnetic separation.	Iron recovery & road sub-base.
Hungary	Mass Burn	Bottom Ash	Magnetic separation.	Iron recovery and use as covering layer at MSW landfill sites.
Japan	Mass Burn	Bottom Ash & Fly Ash	Drying, crushing and ash smelting.	Aggregate for concrete, interlocking block. Sub-base and base course material for road construction.
Nether-lands	Mass Burn	Bottom Ash	Stabilising, ageing.	Construction industry.
Norway	Mass Burn	Bottom Ash	Magnetic separation.	Road construction etc. at the landfill.
Spain	Mass Burn	Bottom Ash	Magnetic separation, ageing, grading, screening & grinding.	Iron recovery & road sub-base.
Sweden	Mass Burn	Bottom Ash	Magnetic separation.	Iron recovery & civil engineering applications.
UK	Mass Burn	Bottom Ash	Magnetic separation	Iron recovery.
	Mass Burn	Bottom Ash	Screening, weathering, stabilisation, encapsulation (with cement and tarmacadam).	Road construction.
	Mass Burn	Bottom Ash	Grading, crushing, screening, magnetic separation.	Fines used for block building. Larger size for asphalt. Oversize sent to landfill. Metal fraction recovered.

Table 6.3 Treatment Processes for Recovery and Re-Use Operations

they are to be further utilised. This technique has also been used for mixing APC residues with water in order to make the material more manageable at the landfill face. The handling properties of APC residues are significantly improved, however, the weight of the product increases by around 40%.

6.5 Chemical Processes

Chemical additives, usually phosphates and lime, can be added to the MSW combustion residue to reduce the total availability and release rate of the heavy metal components. As this is a chemical process rather than solidification/stabilisation, the physical characteristics of the residue are not altered. The residue remains a free flowing granular material and the volume of the residue is only slightly increased after treatment. Although the treated residues are generally disposed of to landfill, they could potentially have a number of uses, particularly in the construction industry, as a lightweight aggregate and as road base material[31]. However, at present, chemical extraction methods have been somewhat uneconomical or limited due to technological issues and are not in widespread use. A number of commercial applications have been developed and laboratory and pilot-scale systems are under development or being tested[32]. For example, soluble phosphates have been used in commercial applications as a stabilisation process for diminishing the release of lead from the ash residue. The performance of combined ash samples that have been treated in this manner has been such that, for example, in Canada and the US, treated combined ash samples routinely pass the leaching test used in determining required disposal management practice and are no longer considered a special waste[33]. The use of forced carbonation and use of chelating compounds have also been reported in commercial stabilisation process applications[32].

6.6 Thermal Processes

Techniques for thermal processing of ash residues (sintering, melting or fusion) have been extensively developed at laboratory and pilot scale[32]. Some full-scale investigations have also been carried out, and a number of commercial application technologies are available. Melting and fusion practices do not effectively incorporate halogens, sulphur or carbon and are complicated by the release of volatile metals that can be mobilised into the off-gases. Additional modification of equipment and design can address some of these concerns. Bottom ash fusion or vitrification is currently practised at several facilities in Japan (Table 6.3)[32]. These applications, although tested, are not in commercial use at EfW facilities in Western Europe or North America. Analysis of costs for thermal treatment, judged against alternative ash residue management options, has indicated limited opportunity for process application[31]. However, a number of novel vitrification processes have recently been reported as being economically viable options to landfilling. These include the PermaVIT Vitrification process, which is an adaptable approach for processing a very broad range of non-hazardous, hazardous and radioactive wastes into chemically durable, construction materials[34]. In the TDR vitrification process[35], bottom ash or fly ash is melted into a monolithic glassy/ceramic material that is resistant to leaching when cooled and can be used as construction aggregate or fill material. There is very little value in the glassy residue, but the cost avoidance associated with landfill disposal can be substantial.

6.7 Solidification/Stabilisation

Contaminants contained within MSW combustion residues can be fixed or encapsulated to prevent or reduce the level of leaching. There are a variety of techniques available to achieve this, many of which are used to prepare residues for final disposal or for re-use in construction or civil engineering applications (Tables 6.2 and 6.3). Leachable contaminants in the residues are immobilised through physical encapsulation, although the net effect is to reduce the solubility of some of the main components of the residue streams (hence the term stabilisation/solidification). Stabilisation /solidification processes can be applied more successfully to bottom ash, heat recovery ash and electrostatic precipitator dust from MSW facilities when compared with APC residues[27]. The techniques available are particularly appropriate for the immobilisation of inorganic contaminants such as heavy metals (i.e. lead, cadmium, mercury, zinc, chrome, nickel and copper). The most common stabilisation/solidification process established is a cement-based process, which involves mixing the ash residues with Portland cement (Table 6.2). The resulting hydrating reaction of the cement forms a solid, monolithic material, which significantly reduces the mobilisation of heavy metals. This process can be applied to residues containing a certain amount of variation in composition, however, there are substances which will effect the curing and setting of the cement, e.g. some organic materials, sulphates and borate salts. The solidified materials are either landfilled, used in land reclamation projects or utilised in other civil engineering applications (commonly as a road sub-base material). Pre-treatment of the residue, screening and weathering, is required before solidification if the residues are to be used in a construction application.

Economical solidification and stabilisation processes have been brought to commercial scale and are currently in use for treating the ash residues from some combustor operations. Mixing of materials, moulding, transport, etc. can effect stabilisation/solidification product quality. In some instances, pre-treatment of ash residues may be required prior to application of stabilisation/solidification processes. In addition, there is little information from the field concerning the long-term durability of these materials or of long term leachability behaviour of incorporated species[32]. These processes do not effectively immobilise chloride salts, so that where this is an issue (eg APC residues), utilisation applications may not be advisable due to long term degradation, release of salts, and poor durability of products.

6.8 Summary of Treatment Practices

Present trends and data indicate a preference for use of bottom ash in commercial applications. Difficulties arise with use of other ash residue fractions (fly ash and APC residues) due to poor performance or potential concerns for mobilisation of elements incorporated in products. Various techniques have been developed aimed at improving MSW ash residue properties to allow beneficial use or to fix the contaminants in the residue matrix, thus leading to less stringent disposal regimes and lower environmental impact. These treatment techniques include crushing, weathering, separation processes, mixing, chemical processes, thermal processes and solidification/stabilisation of the ash residues.

For bottom ash, pre-treatment techniques to screen oversized components, to remove ferrous metal and to allow weathering of the material are recognised low cost procedures for improving the chemical integrity and structural durability of the material prior to disposal or re-use applications. There is little evidence of widespread use of treatment techniques, such as solidification/stabilisation of the bottom ash (except for use as compacted granular base), due to additional processing requirements and higher processing costs.

Utilisation options for fly ash and APC residues are limited due to their fine particle size and the presence of relatively high levels of contaminants (Section 7). Most IEA/ISWA member countries classify these materials as hazardous waste and are moving towards stricter disposal regulations for these materials. Current management practices typically involve disposal of the untreated residue at a fully contained monofill site or pre-treatment of the residue prior to disposal in a conventional landfill (Section 8). Because of the higher costs for disposal of hazardous wastes and, in certain countries, prohibition of landfilling of untreated fly ash and APC residues, pre-treatment of the residues (using processes such as solidification/stabilisation) prior to landfilling is becoming the preferred management option.

The implementation of the various pre-treatment and treatment techniques in the short and long term depends on the costs per tonne and the beneficial application of the end products. Techniques such as crushing, weathering, separation and mixing, are relatively inexpensive compared to those involving thermal, chemical and solidification/stabilisation. Because residues can vary among installations (depending on the nature of the waste processed, the EfW combustion process and ash handling system) the suitability of the available techniques will be specific for each combustor. A brief description of experience of ash treatment practices in the Netherlands and the UK is given below.

Dutch Experience

In the Netherlands, bottom ash from EfW facilities is widely used in the construction industry. However, the introduction of the strict environmental demands as presented in the 'Building Materials Decree' require the development of new techniques to improve the environmental quality of MSW bottom ash[36]. The current environmental quality of bottom ash does not meet the requirements as formulated in the 'Building Materials Decree' with respect to the leaching behaviour of copper, molybdenum, antimony and bromide. Although practical uses remain possible within the boundaries of future regulatory demands, the required precautions (such as the use of polyethylene and sand-bentonite liners) will probably weaken the competitiveness of MSW bottom ash in the market. By improving the environmental quality of MSW bottom ash for use in building materials, its market-share can be secured. Methods for quality improvement include the use of stabilising additives and/or the accelerated ageing of MSW bottom ash. Some proprietary products, such as WES-PHx®, have been developed but in most cases the mixture of chemicals needs to be adapted to the specific ash type and the given environmental conditions[31].

Dutch legislation has prohibited landfilling of untreated MSW fly ash since 1998. In general, Dutch APC devices are flue gas scrubbers which produce residues with moderate leaching behaviour compared to fly ash and come under a lower hazardous waste categorisation[36]. However, because of the high costs for disposal of hazardous wastes, a financial incentive exists to improve the environmental quality of APC residues to that of a less hazardous waste category. Hence, improvement of the environmental quality of fly ash and APC residues has been required in the Netherlands in order to increase their uses as well as to be able to continue landfilling the remaining fraction. The following options for improving the quality of MSW fly ash have been considered:

- *Cold solidification (fly ash and APC residues)*: Cold solidification (i.e. below 200^{o}C) involves the fixation of heavy metals, usually by employing cement and additives, in order to reduce their leachability. Under more favourable conditions, cold solidificates could be used as building materials.

- *Washing (+cold solidification):* For fly ash; soluble salts, such as chlorides and bromides, cannot be fixated using cold solidification techniques. A washing step prior to the solidification may solve the problem of soluble salts. For APC residues; those EfW facilities that are not allowed to discharge their waste water make use of spray-drying techniques. Spray drying results in a product that consists mostly of salts. Upon spray drying, the waste-water is injected into hot flue gas. The flue gases contaminate the resulting dry salt with heavy metals. A subject being investigated is the manner in which this product could be separated into a clean salt fraction and a contaminated heavy metal-containing filter-cake. The purified salt fraction could possibly be reused or discharged into the sea.

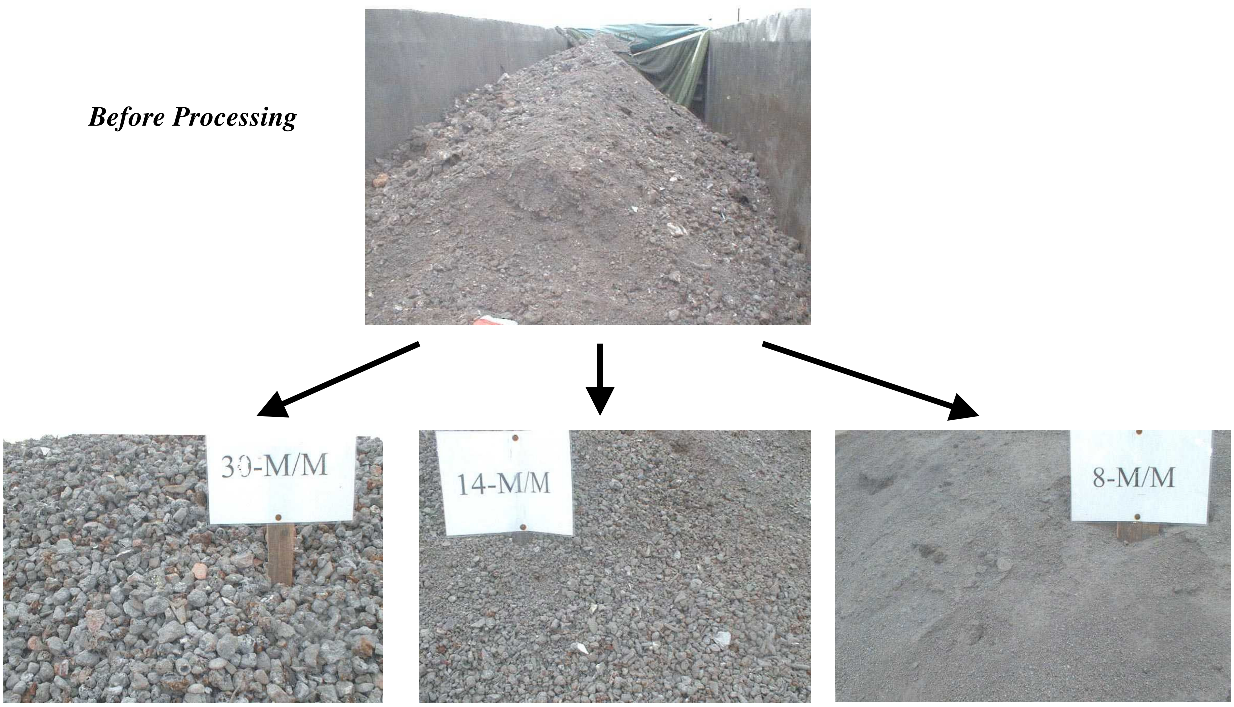
- *Thermal treatment (fly ash)*: Usually melting processes are what is meant when the phrase is used to describe fly ash treatment. Sintering processes, as well as thermal treatment techniques, are thought to be inappropriate for fly ash treatment since the improvement in quality in insufficient. The high operating temperatures of melting processes, at least 1300^{o}C, require a great deal of energy and expense. It is therefore generally accepted that melting techniques are only cost-effective if the products can be used in a practical way. The quality of the melting products is considered, therefore, in conjunction with the standards for building materials rather than those for landfilling.

UK Experience

In the UK, an EfW plant has a long term contract to process and market the production of MSW bottom ash, which is currently 140,000 tonnes per annum (Figure 6.1). The contractors have a quality management system and process the bottom ash to meet customer needs (Figure 6.2). The processed ash is being sold to a broadening customer and applications base for use as sub-bases and road bases on heavy pavements. For example: highways, ports, airports, container terminals, retail parks and warehouses.

Figure 6.1 Typical Ash Processing Plant (Edmonton, London)

Before Processing



After Processing

Figure 6.2 An Example of the Different Grades of Ash Available

7 UTILISATION OF MSW ASH RESIDUES

Efforts to utilise ash residues in various applications are carried out world-wide. Interest in utilisation is principally motivated by the potential for (i) extending existing ash landfill capacity (and thus reducing disposal costs) and (ii) the ability to create from ash residues value-added products that conform to regulatory requirements for management and use (such as the substitution for natural aggregates). To date, effort has concentrated on the re-utilisation of bottom ash residue, where this material can be used as an alternative aggregate material for civil engineering applications, such as base and sub-base for roadways. The two fundamental concerns with using MSW ash residues in applications are that (i) the physical and chemical properties of the ash residue/product are appropriate for the intended application (i.e. bearing capacity, compaction, etc.), and (ii) the application does not lead to environmental degradation. The latter situation relates mainly to the leaching of metals and salts from the ash, since the potential loading of ash within a fill application may pose a potential problem. Many countries have considered the environmental implications of these uses and have developed guidelines for implementation. While the utilisation practices for ash residues are discussed in Sections 7.2 and 7.3, a brief discussion of existing regulations governing the use of residues is given in Section 7.1.

7.1 Regulations for Residue Recovery and Re-Use Operations

The chemical and physical characteristics of ash residues from waste combustion plant vary considerably (Section 4). This variability has been one of the major barriers to the acceptance of MSW derived ash residues in re-use applications. In addition, the presence of contaminants in the ash can lead to poor environmental performance and may also have an adverse effect on the product performance. In order to promote the idea that MSW ash residues can be a predictable commodity, many countries have adopted requirements for use of ash residue products in contemplated applications. These requirements for good performance are based on (i) the properties of the ash residues (including standard engineering criteria) and (ii) the potential for environmental impact during product application lifetime. For example, alkali metals and chlorides in ash residues need to be limited for concrete and cement applications since they give rise to loss of strength and risk of corrosion in reinforcement bars. Another area of concern is the potential for the presence of higher levels of heavy metal concentrations in the fly ash and APC residues. In many IEA/ISWA member countries, regulations and specification standards are used to address these issues. Table 7.1 outlines the various specification standards for re-use applications in IEA/ISWA member countries and brief descriptions of existing regulations in the Netherlands and France are given below. The aim of these specifications and regulations is to set minimum requirements for the performance of ash residues in laboratory conditions.

Dutch Experience

In the Netherlands, the use of bottom ash from MSW facilities in construction applications amounts almost to 100% of that produced. Working together through an industrial association, EfW facilities have encouraged the introduction of regulatory standards governing the useful application of bottom ash. These regulatory measures have been endorsed by the Dutch governmental authorities[36]. Ashes from hazardous waste treatment plant and APC residues are not permitted for use in construction under this scenario. Standards have been set dealing with the weathering of the ash and maximum levels of contamination. In addition, high standard upgrading techniques have been applied in order to obtain a consistent construction material which meets the physical and performance requirements demanded by the market. The key physical characteristics for bottom ash have been agreed with the Dutch road contractors association. Certification has been introduced to guarantee environmental quality and the physical characteristics of the ash.
The certification applies to:

Country	EfW Technology	Residue Type	End-Use Market	Re-Use Applications	% Residue Utilised in 2000[1]	National Standard
Austria	**Mass Burn**	Scrap Metal	Iron	Iron smelting.	n.d.	n.d.
Belgium	**Mass Burn**	All Residues	Not Re-used		0	
Canada	**Mass Burn**	Bottom Ash	Civil Engineering	Road sub-base.	100	Standard specifications for highway construction
		APC	Not Re-used		0	
		Treated APC	Not Re-used		0	
Finland	**Mass Burn**	All Residues	Not Re-used		0	
France	**Mass Burn**	Bottom Ash	Civil Engineering	Road sub-base.	>50%	Department Order of 25/1/91 on MSW combustion plants (article 14)
Japan	**Mass Burn**	Bottom Ash	Civil Engineering	Sub-base and base course material for road construction; aggregate for concrete and interlocking block construction; brick manufacture.	n.d.	Asphalt pavement outline; JIS A 5406; JASS-7 M 101; JIS R 1250
Nether-lands	**Mass Burn**	Bottom Ash	Civil Engineering	Embankment fill; road-base material; aggregate for asphalt; aggregate for concrete building blocks; daily cover material for landfills; and noise or wind barriers.	>90	Standard specifications for re-use
		Fly ash	Civil Engineering,	Asphalt filler, mine reclamation, top sealing of landfill sites.	38	Standard specifications for re-use
Norway	**Mass Burn**	Bottom Ash	None at present - Civil Engineering in future		0	
		Fly Ash & APC	Not Re-used		0	
Spain	**Mass Burn**	Bottom Ash / Ferrous fraction	Building and Civil Engineering; Metallurgic Industry (ferrous fraction)	Road sub-base and embankment; Lightweight aggregates for construction material, filling material etc.; Ferrous fraction used in smelting plant.	25 (0 to 95)	Department de medi ambient-generalitat de Catalunya - 15 Feb 1996
Sweden	**Mass Burn**	Bottom Ash / Ferrous fraction	Building; Metallurgic Industry (ferrous fraction)	Slag used in railway station construction; Ferrous fraction used in smelting plant.	20 (0 to 100)	n.d.
UK	**Mass Burn**	Bottom Ash/ Ferrous fraction	Civil Engineering; Metallurgic industry (ferrous fraction)	Substitute aggregate/building block; Road sub-base and wearing surface; Concrete block manufacture; Coated material component; Ferrous fraction used in smelting plant.	40 (0 to 100)	BS 3797 (1990) for Lightweight aggregate.
		Fly Ash & APC	Not Re-used		0	
	FBC	Fly Ash & APC	Not Re-used		0	

n.d. - no details given [1] *Estimate of average % of residues which were re-used; (range of % utilisation of individual plants)*

Table 7.1 Markets and Standards for Waste Combustion Residues

Environmental Quality; Leached Concentrations	Physical Aspects
• Arsenic (As) <50 mg/l • Cadmium (Cd) <50 mg/l • Chromium (Cr) <5,000 mg/l • Copper (Cu) <5,000 mg/l • Nickel (Ni) <5,000 mg/l • Lead (Pd) <5,000 mg/l • Zinc (Zn) <20,000 mg/l	• Iron content (<5% m/m) • Combustible material (<6%m/m) • Digestible material (<2% m/m) • Free of fly ash • Fraction <63 µm (<8% m/m) • Crushing-resistance factor (>0.65) • At least 6 weeks storage prior to use • Additional granulatory demands

Some restrictions are applied to the placement of the ash but these are broadly similar to those for several other secondary aggregates and are set out in a code of practice. It has been an important factor in the market acceptance of bottom ash that public authorities have acted as pioneers in its use. The guidelines and regulations have been shown to influence civil engineering decision makers to accept the ash in place of sands and gravels. Marketing has also proved to use the ash which may otherwise be overlooked by designers and specifiers.

Dutch legislation designates MSW fly ash as a hazardous waste. Furthermore, the leaching of a range of heavy metals exceeds the maximum levels that are allowed for building materials. The present use of fly ash as an additive in fillers for asphalt, however, does meet the environmental demands in the 'Building Materials Decree'[36]. This is due to the fact that bitumen encapsulates the fly ash particles and only 2% of fly ash is present in the asphalt. MSW fly ash is also used in concrete applications, but requires pre-treatment prior to application, due to its high chlorine content.

French Experience

France currently utilises 45% of the bottom ash in road beds, however, this may change due to recently introduced regulations[15]. Bottom ash destined for a utilisation application must meet criteria in relation to combustible content and leaching characteristics. The LOI content must not exceed <5% and the leachates should not exceed the levels given below. The material will still require ferrous removal, screening and ageing.

Requirements for Bottom Ash Utilisation - Leaching (mg/kg unless noted)							
Total Soluble Solids	As	Cd	Cr^{+6}	Pb	Hg	SO_4	TOC
<5%	<2	<1	<1.5	<10	<0.2	<1.0%	<1500

UK Experience

In the UK, the Energy from Waste Association (EWA) is co-ordinating the development of the use of bottom ash as a secondary aggregate. They consider that successful marketing and use of the product will be achieved through satisfying both the regulatory bodies (e.g. the Environment Agency) and customers that there is "no risk of harm to human health or the environment". A subgroup of the EWA, the "Ash Working Group", has developed a protocol for characterisation and routine testing of ash. There is also an exchange of information on the uses for bottom ash[14].

7.2 Bottom Ash Re-Use Applications

Bottom ash from mass burn EfW treatment facilities is considered to have the greatest potential for utilisation because it typically has the lowest content of leachable metals of concern (e.g. lead, cadmium, mercury etc.) and soluble salts. In addition, this ash fraction has physical properties similar to lightweight aggregates and represents over 80 weight percent of the total residues generated. Consequently, to date, most of the effort has been made on bottom ash utilisation projects, where this material can be used as an alternative aggregate material. Although steps could be taken to improve the quality of this material by removing the boiler ash and grate riddlings fraction, the overall improvement in quality is generally considered to be minimal and not worth the additional preparatory effort. Tables 7.2 and 7.3 show the current status of MSW combustion residue utilisation, whilst Figure 7.1 compares the amount of waste treated in EfW combustion plant with the amounts of waste residue generated and utilised. A summary of the re-use applications for waste combustion residues is presented in Table 7.4.

Country	Utilisation Data	Applications
Canada	• 100% utilised in 2000 (projected).	• Landfill intermediate cover. • Road sub-base.
Denmark	• 420 000 tonnes of bottom ash produced annually. • Over 90% of bottom ash utilised.	• Granular sub-base for car parks, bicycle tracks, paved and unpaved roads.
France	• Approximately 3 million tonnes of bottom ash produced annually. • Over 50% of bottom ash utilised with the remaining landfilled or stockpiled testing following weathering.	• Untreated material used for foundations for low traffic bitumen roads or as sub-foundation layer on high traffic roads. • Weathered bottom ash can be considered for use as basal material overlying the foundation layer for roads.
Germany	• Approximately 50% of bottom ash is utilised.	• Paving applications (granular base). • Pilot-scale use of APC residue grout in coal mines (50,000 tonnes).
Hungary		• Covering layer at MSW landfill sites.
Japan		• Aggregate for concrete interlocking block. • Sub-base and base course material for road construction.
Netherlands	• Over 0.9 million tonnes of bottom ash produced annually. • Over 90% of bottom ash is utilised, with 55% meeting Dutch QA/QC criteria. • To date, over 2 million tonnes of bottom ash utilised. • Approximately 40% of fly ash utilised.	• Bottom ash used as aggregate in asphalt and concrete. • Bottom ash used as granular base or fill in road base, embankments, noise and wind barriers. • Fly ash used as a filler in asphalt applications.
Norway	• 0% used at present.	• Road construction etc. at the landfill.
Spain	• 25% (0-95) of bottom ash is utilised.	• Iron recovery. • Civil Engineering applications.
Sweden	• Utilisation of bottom ash under development.	• Pavement applications.
UK	• 40% of bottom ash is utilised.	• Road construction. • Fines used for block building, larger size for asphalt and oversize is sent to landfill.

Table 7.2 Summary of MSW Combustion Ash Residue Utilisation

Country	Estimates of Annual Tonnage of Waste Residue Utilised			% of Waste Residue Utilised*		
	Bottom Ash	Fly Ash	APC Residue	Bottom Ash	Fly Ash	APC Residues
Denmark (1994)	>380,000	-	-	>90	-	-
France (1999)	>1,500,000	-	-	>63	-	-
Germany (1996)	1,280,000	-	20,000	60	-	15
Netherlands (1996)	950,000	34,000	-	>90	40	-
UK (1999)	250,000	-	-	40	-	-

** % waste residue utilised / waste residue generated.*

Table 7.3 Utilisation of MSW Combustion Ash Residues[15, 27]

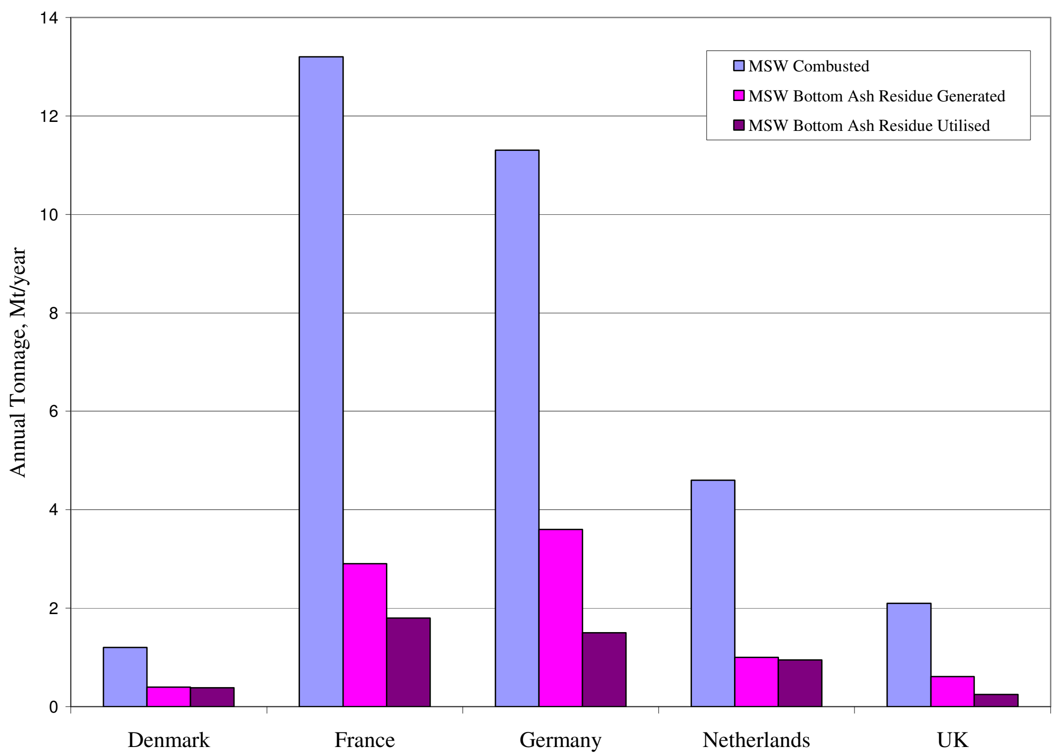


Figure 7.1 Production and Utilisation of Bottom Ash Residues from EfW Combustion Plant

Waste Material	End Product Use	Comments
Bottom Ash	Road Construction: • Base Course • Asphalt Pavement • Embankment	 Used in cement stabilised bases. Larger sizes used as filler for asphalt. Used as granular base.
	Landfill Cover	Requirements for coarse material are categorised according to permeability and/or particle size distribution.
	Building Construction	Lightweight aggregate for construction material, filling material, interlocking blocks and concrete blocks. Railway station construction.
Ferrous Fraction of MSW Ash Residue	Metallurgic Industry	Ferrous fraction recycled in a smelting plant.
Fly Ash	Civil Engineering	Asphalt filler, mine reclamation and top sealing of landfill sites. Concrete applications but requires pre-treatment, due to high Cl content.
APC Residues	Civil Engineering	Potential for use as grout in coal mines.

Table 7.4 Summary of Re-Use Applications for Waste Combustion Residues

In summary, applications using bottom ash without further treatment (other than weathering or screening of oversized material and ferrous metal) as an aggregate replacement in asphalt used for binder or base courses for road/pavement construction currently appear to have the most potential. Incorporation of bottom ash into asphalt results in a significant reduction in potential contaminant release. Further emphasis is given to these applications because both would have an impermeable asphalt layer above the utilised material, if not both above and below. Lower priority is given to the use of bottom ash in the wearing course because of potential abrasion and direct environmental exposure. Concern also exists about dust generated during milling of the wearing course during maintenance and re-paving operations. Use of granular material in embankments is also limited except in locations where salt release would not constitute a problem or if other precautions to limit salt release are established. In general, use of granular material directly as the wearing course is considered unacceptable and use of ash incorporated into asphalt for embankments is not considered a practical option because asphalt based materials are not typically used in that application.

Other potential applications for MSW bottom ash include embankment fill; aggregate for concrete building blocks; daily cover material for landfills; and noise or wind barriers. A brief description of experience in key European countries and the USA is given below, whilst details of specific case studies for re-use applications of MSW ash residues in the UK, the Netherlands, Sweden, Denmark, Canada and USA are given in Appendix I of this report.

UK Experience

In the UK, the EWA is co-ordinating the development of the use of bottom ash from EfW facilities as a secondary aggregate. They consider that successful marketing and use of the product will be achieved through satisfying both the regulatory bodies (e.g. the Environment Agency) and customers that there is no risk of harm to human health or the environment. A subgroup of the EWA, the 'Ash Working Group', has developed a protocol for characterisation and routine testing of ash. There is also an exchange of information on the uses of bottom ash.

Dutch Experience

Over the past few years in the Netherlands, almost all of the bottom ash generated in EfW facilities treating MSW is used in construction applications and only a marginal amount of bottom ash was sent for landfill. An important factor in the market acceptance of bottom ash was that public authorities have acted as pioneers in its use. Regulatory standards governing the useful application of bottom ash have been introduced and high standard upgrading techniques have been applied in order to obtain a consistent construction material which meets the physical and environmental performance requirements demanded by the market (Section 5). The main application areas for bottom ash are as embankment fill; road-base material; aggregate for asphalt; aggregate for concrete building blocks; daily cover material for landfills; and noise or wind barriers.

Other European Experience

In Denmark, size-fractioned, processed bottom ash has been used for development of granular sub-base for parking lots, bicycle paths, paved and unpaved roads, and a number of smaller projects. Similarly, granular sub-base paving applications have been carried out in Germany. Sweden has used bottom ash in pavement applications.

American Experience

In the USA a number of demonstration or small scale projects (artificial reefs, cement blocks, road and sub-base, etc) have been carried out[32]. Bottom ash and combined ash are being considered for use in paving applications (granular base and aggregate in asphalt), for use in building construction or reef development, and for use as daily or final cover at MSW landfill disposal sites. Some limited applications are being carried out at present, despite various regulatory uncertainties, which are expected to be resolved.

7.3 Fly Ash and APC Residues Re-Use Applications

Utilisation of fly ash and APC residues is limited due to their high soluble salt content and relatively high content of metals of concern, such as cadmium, lead, zinc and mercury. In addition, the high content of fine-grained particles gives it high moisture holding capacity and therefore susceptible to frost expansion, and is difficult to compact. In the Netherlands, fly ash is used on a commercial scale in fillers for asphalt and has shown potential for uses as a filler, or pozzolanic additive, in concrete. In Germany, use of fly ash and APC residues as a grout in coal mines has also been investigated at pilot plant scale. Descriptions of these applications are outlined below.

Dutch Experience

Dutch legislation designates MSW fly ash as a hazardous waste. Furthermore, the leaching of a range of heavy metals exceeds the maximum levels that are allowed for building materials. The present use of fly ash as an additive in fillers for asphalt, however, does meet the environmental demands in the 'Building Materials Decree'[36]. This is due to the fact that bitumen encapsulates the fly ash particles and only 2% of fly ash is present in the asphalt. On average 20% of the fly ash is used in this way[36]. Due to the limited capacity of the market for asphalt, and hence asphalt fillers in the Netherlands, the re-use figures of fly ash cannot increase substantially unless other uses are developed. Pre-treated MSW fly ash can also be used in concrete, (i) as a filler to obtain high density concrete (ii) as a partial cement replacement; and (iii) as a high value additive after further size reduction. The applicability of fly ash as concrete filler depends strongly on the quality and variability of the residue, which in turn depends on the MSW from which the fly ash originates and the EfW combustion process. The potential applicability of fly ash increases for EfW treatment facilities with a constant fly ash quality containing low levels of contaminants.

German Experience

In Germany, APC and fly ash residues are undergoing pilot-scale and provisional evaluation for use in the coal mining industry as filling and sealing materials for excavation cavities, and as aggregate substitute in grouts[15]. The hard coal mines of Ruhrkohle AG consume approximately 1.5 million tonnes of grout per year and the potential capacity to incorporate APC residues in grouts is approximately 20,000 tonnes/yr. Approximately 50,000 tonnes of APC residue has been used for a pilot test of mine filling and sealing operations. Certain APC residues also are being considered for use in alinite cement. In this case, the APC residue is used as a substitute for lime as a raw material. APC residues are pelletised with other raw materials and about 20% water, and then treated in a rotary kiln to form an alinite cement clinker which is subsequently ground into cement.

7.4 Constraints for Ash Residue Utilisation

The principal constraints to the development of viable utilisation options are the potential for the release of contaminants through leaching or dust emission, the amount of processing required and the quality control (i.e. chemical and physical property variability) of the residues. Bottom ash is considered to have the greatest potential for utilisation, and in many countries, pre-treatment techniques to screen oversized components, to remove ferrous metal and to allow weathering of the material are recognised low cost procedures for improving the chemical integrity and structural durability of this material. There is little evidence of widespread use of treatment techniques, such as solidification/stabilisation of the bottom ash, due to higher processing costs. As awareness of the need to pre-treat residues increases, the key to utilisation will be the relative cost of disposal versus utilisation. If landfill prices (and taxes where levied) rise significantly, alternative outlets will be actively sought.

8 ASH RESIDUE DISPOSAL PRACTICES

Disposal practices for ash residues from EfW treatment facilities vary widely across the world. Substantial variations in disposal practices are also found within countries consisting of federations of states or provinces, such as US, Canada and Germany. Landfilling may involve dry storage (entombment or containment), containment with leachate collection, controlled contaminant release or uncontrolled leaching[32]. Regulations governing the disposal of MSW ash residues in landfills have been developed, to ensure that the landfilled waste does not cause any unacceptable short or long term impacts on the environment or on human health. The objective of these regulations is to reduce the reactivity of materials being placed in landfills. Potential for, and impacts of, leaching of contaminants is a principal concern. For fly ash and APC residues there is also the potential for release of fugitive dust. However, this problem can usually be avoided or controlled with proper precautions, such as dampening with water.

8.1 Disposal of Bottom Ash

The bulk of the residue generated at a MSW treatment facility consists of bottom ash. In the majority of IEA/ISWA member countries, bottom ash is handled separately from the other residue streams. Ash residue that cannot be economically utilised in conformance with technological or regulatory requirements is disposed of by landfilling, and regulations governing this activity have been developed. Monofill represents the most common method of bottom ash disposal in Europe and Canada, although co-disposal of MSW ash residues with other wastes, including MSW, does occur[15]. The strategies employed for disposal of bottom ash vary and include:

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

At present, the prevailing disposal strategy for bottom ash is containment with some type of leachate collection. In the majority of countries, bottom ash is classified as non-special waste and passes the national landfill regulations without pre-treatment requirements (Table 5.1). In Austria and Hungary, however, bottom ash from mass burn EfW facilities are categorised as special waste and incur stricter landfill regulations for hazardous waste category. In Austria, bottom ash is sometimes pre-treated to immobilise the contaminants in the residue, prior to disposal in a lower category of landfill.

The main restriction on the disposal of bottom ash is the availability of void space and appropriate planning permission. Landfills usually require some containment and minor operational constraints may apply if the landfill is sited within the catchment of a groundwater source. Bottom ash from MSW EfW treatment facilities is often used as landfill cover (Section 7). Brief descriptions of experience of disposal practices for bottom ash in Sweden, France, the UK and Germany are given below.

Swedish Experience

In Sweden, bottom ash is disposed of in a dedicated monofill space in an approved disposal site. Each site has its own permit requirements, which were approved by the Environmental Franchise Board[15]. Furthermore, monofills that are used for bottom ash and APC residues must dispose of these streams in separate cells. Current recommendations suggest that leachate be collected for the initial filling period and after this time infiltration should be kept below 50 mm/year by the use of proper soil covers.

French Experience

France has a landfill regulation, which suggests that landfilling is the last resort after all recyclable uses have been made of the material[15]. This encourages treatment of waste in EfW facilities after recycling and utilisation of residues where appropriate. Any material landfilled must contain less than 5% organic matter and the total organic carbon content of the leachate is limited. The act stipulates categories of materials according to its solubility. A material can be recycled if the solubility is less than 3%. There are two classes of landfills: Class 1, Hazardous Waste with a solubility greater than 5% and less than 10%; and Class 2 where the material has a solubility less than 5%. All landfills have to be lined.

UK Experience

In the UK, bottom ash is disposed of at licensed landfill facilities that can handle the material. Licensing requirements reflect the need to preserve the environment and ensure that neither the water resources nor public health are endangered by the disposal practice. Bottom ash is handled as a contaminated soil and is deposited in lined pits where the effluent produced is removed. Bottom ash is often used as cover material in older landfill sites.

German Experience

In Germany, landfill disposal of materials requires that the residues meet a loss on ignition criteria of less than 10% and contain less than 10% soluble salts. Furthermore, leachate from the residue must meet criteria for various trace metals based on elution with distilled water. In 1993, the German Bundesministerium für Umwelt issued a new directive on landfills used for both MSW and waste ash residue disposal[2]. This legislation defines two classes of landfills based on the total organic carbon, loss on ignition at 550^{o}C, leachate quality as defined by DEV S4, and solubility. After simple in-plant treatment, bottom ashes from properly operated waste treatment plants can meet the criteria and is disposed of in a Type 1 landfill.

8.2 Disposal of Fly ash and APC Residues

Fly ash and APC residues are more controversial and options for handling and disposal are more limited than that of bottom ash. Their potentially hazardous nature is due primarily to their higher levels of volatile toxic metals and fine particle size. Metals that have low boiling points (cadmium, zinc, lead, mercury, etc.) tend to concentrate and accumulate in the fly ash and APC residues, and the ash will frequently fail the National regulatory landfill toxicity/leaching tests. The majority of IEA/ISWA Member countries are moving toward stricter disposal regulations for fly ash and APC residues. In certain countries, disposal of untreated special (hazardous) wastes (e.g. fly ash and APC residues) is being restricted to mono-filling at fully contained landfills situated on non-aquifiers. Whilst in others (such as the Netherlands, Japan, Norway, Sweden, Spain, France), landfilling of untreated fly ash and/or APC residues has been prohibited. These residues require pre-treatment, such as solidification and stabilisation, to improve their environmental quality prior to disposal. These pre-treatment practices are discussed in Section 6.

Canadian Experience

In Canada, disposal options for fly ash and APC residues include transfer to a hazardous waste disposal facilities or treatment of the residues prior to disposal. Various treatment alternatives from disposal in secure landfills to solidification have been considered, but there are few regulations in place to evaluate the efficacy of a treatment process. The exception is in British Columbia, where the treated ash must pass a battery of laboratory tests prior to disposal in a conventional landfill. The testing protocol includes evaluating the treated residue using chemical engineering, durability and leaching tests. One treatment practice currently being used in commercial applications is based on a stabilisation process and aims to reduce the release of leachable metals from the fly ash and APC residues. The treated ash residues routinely pass the standard leaching/toxicity tests used in determining required disposal management practice. The treated ash can then be disposed of as for the bottom ash, thereby avoiding high landfill taxes incurred by the special waste category[33].

French Experience

The 1991 French law on MSW EfW treatment adopted the EEC directive on air emissions but has tighter mercury and cadmium standards. This has resulted in an increase use of wet APC systems, and hence, more sludge from these systems. The changes in regulations have fostered increased study into ways of modifying these residues to meet the disposal criteria. Immobilisation of contaminants by solidifying with hydraulic binders is being practised in some areas, and vitrification alternatives are being investigated.

Danish Experience

In Denmark, fly ash and APC residues (from dry or semi-dry processes) are disposed of in dedicated monofills with leachate collection systems and bottom liners, and often with impermeable cover layers. Wet scrubber sludges are generally monofilled alone or are mixed with fly ash residues. All of these measures are only considered temporary solutions and suitable treatment processes are preferred.

German Experience

In Germany, the APC system has to be designed in a way to minimise the production of harmful residues. Heat recovery system ash is separated from dry/semi-dry scrubber residues in some facilities. The fly ash and APC residues are disposed in either approved landfills or preferably in underground disposal sites, such as old salt mines or in special cells or MSW disposal sites. To minimise the release of dust from surface stored materials, it is packaged in large bags or moistened.

8.3 Disposal of FBC Residues

There were no reports of any re-use applications for FBC waste ash residues. In Japan and Spain, fly ash from FBC waste combustors are landfilled without pre-treatment (Table 6.2). In Sweden APC residues from waste FBC plant are moistened and compacted in the landfill, whilst in the UK, APC residues are acid neutralised and landfilled in a dry state.

9 ECONOMICS

9.1 Costs of Disposal to Landfill

The preceding section of this report describes the current practices for disposing of ash residues from waste combustion plant. In general, bottom ash which is not utilised is sent directly to landfill, whilst APC residues and fly ash either require treatment on site, or they must be disposed as a hazardous waste largely because of their leaching characteristics and trace metal content. The costs of disposing of waste ash residues include a number of components, such as waste (or landfill) tax, treatment costs, containment costs, transport costs etc. Costs for disposal of both types of waste ash residues in IEA/ISWA member countries are presented in Table 9.1. Local tipping or gate fees for waste ash residues are highly dependent on regional market conditions and have not been included in the table. The response from EfW operators was limited due to confidentiality issues regarding economics of ash residue recovery, re-use and disposal.

In the majority of IEA/ISWA member countries, regulatory constraints on the routes for disposal of wastes exist, which are closely related to the classification of the waste in terms of their pollution potentials. Hazardous or special waste incurs stricter landfill regulations than non-special waste, requiring disposal in a higher category of landfill with higher landfill tax charges. In the UK, for example, the operators of licensed landfill sites have been obliged to pay tax on waste entering the site since 1996. There are currently two rates. The higher rate of 15€ per tonne applies to all wastes except inert wastes, which are charged at 3€ per tonne. From May 2000 the 15€ rate will increase to 16.5€, and annual increases of 1.5€ will bring the rate to 22.5€ by 2004. However, a landfill tax (of around 28.5€) currently being introduced in Sweden, will be applied all waste residues independent of the waste residue categorisation.

In the EU, a number of different types of waste taxes exist. Waste taxes can be *cost covering charges* where the revenues are used either to pay for waste disposal services, such as the Dutch household waste tax based on the amount of waste collected or the size of household, or to finance recycling services, such as the Swedish battery charge[37]. Or, they can be *incentive taxes* levied to change environmentally damaging behaviour. Revenues are often used to further encourage behavioural change. One example is the German toxic waste charge, which is dependent on the potential danger of the waste and its cost of treatment[37]. The third way that a waste tax can be used is as *a fiscal environmental tax*, whereby surplus revenues from the tax can be used to finance budget deficits or shift taxes from labour to resources. Such a change in the tax system, which shifts taxes away from labour and capital and onto the use of resources, is known as an ecological tax reform (ETR). An example is the UK's landfill tax which aims to cut waste, to get more of it reused or recycled and to boost employment. Clearly, these three types of taxes are not mutually exclusive; a cost-covering charge may have incentive effects, as may a fiscal tax, or revenues from a fiscal tax may be partially used for environmental purposes.

9.1.1 Bottom Ash

Disposal costs for bottom ash vary significantly for the different IEA/ISWA member countries. The main variant is the waste/landfill tax, which ranges from 2€ per tonne of residue in the Spain to 112.5€ per tonne of residue disposed to landfill in Austria (Table 9.1). The higher disposal costs for bottom ash in Austria are partly due to its categorisation as a special waste, which incur stricter (and more expensive) landfill legislation. Transport costs are site specific and ranged from around 3€ to 7.5€ per tonne of residue. Treatment costs were negligible, resulting in total costs for disposal of bottom ash residues ranging around 7.5€ to 180€/tonne. In Spain, one operator of a FBC plant quoted disposal costs as low as 5€ per tonne of bottom ash.

Country	Residue Type	Disposal Cost Breakdown, € per tonne of residue					Total
		Landfill Tax	Treat-ment	Contain-ment	Transport	Others	
Austria	Bottom Ash	112.5			3.75		**116.25**
	APC	88.5			3.75		**92.25**
	Fly Ash	124.5			3.75		**128.25**
Canada	Bottom Ash				3.75		**>3.75**
	APC						**77.25**
	Treated APC		49.5				**71.25**
France	Bottom Ash						**7.5– 52.5**
	APC	112.5	112.5				**225***
Japan	Bottom Ash						**180**
Nether-lands	Bottom Ash		3 – 4.5				
	Fly Ash/APC						**75 - 120**
Norway	APC	75			60		**135**
Spain	Bottom Ash	30			7.5		**37.5**
	APC	55.5 - 150			6 - 15		**61.5 - 165**
	B.A. (FBC)	2			3		**5**
	APC (FBC)	41.25		5	10.6		**56.85**
Sweden	Bottom Ash	10.5			4.5		**15**
	APC/Fly Ash	36			11.25		**47.25**
	APC/F.A.(FBC)						**28.5**
UK	Bottom Ash	3		21			**24**
	APC	15		58.5			**73.5**

** Excluding transport costs* *B.A. Bottom Ash* *F.A. Fly Ash*
Bottom ash, fly ash and APC residues are from mass burn plants unless stipulated otherwise.

Table 9.1 Costs of Disposal to Landfill

9.1.2 Fly Ash and APC Residues

Disposal costs for fly ash and APC residues include a further component, treatment process costs; the economics of which varies with the treatment method. Costs for treatment of APC residues ranged from 49.5€/tonne for a process involving stabilisation with phosphoric acid, to 112.5€/tonne residue for solidification in concrete. Landfill taxes also varied significantly from 15€/tonne in the UK to 124.5€/tonne of fly ash residue disposed to landfill in Austria. In general, transport costs were higher than for bottom ash residues and varied from 3.75€/tonne to 60€/tonne of APC residue. Total costs for disposal of APC residues and fly ash to landfill ranged from 47.25€/tonne to over 225€/tonne of residue.

Disposal costs for APC residues and fly ash from FBC waste combustors in Spain and Sweden were around 57€/tonne and 28.5€/tonne of residue respectively.

A brief comparison of the relative costs of disposal of untreated and treated fly ash and APC residues from mass burn EfW plants in Canada and France is given below.

Canadian Experience

In Canada, the use of soluble phosphates in commercial applications as a stabilisation process for diminishing the release of lead and other metals from ash residues has been demonstrated to be an economically viable option. Total disposal costs for treated APC residues are typically 71.25€/tonne of residue. This compares with 77.25€/tonne for disposal of untreated APC residues in special cells at the landfill site. The cost benefits incurred from down grading of the waste disposal categorisation for treated APC residues, from special to non-special waste, outweighs the treatment costs of some 49.5€/tonne of residue.

French Experience

In France, landfilling of untreated fly ash and APC residues is prohibited due to their potential environmental impact. Solidification/stabilisation of the residues currently represents the most common treatment method to improve their environmental quality prior to disposal. Total disposal costs quoted for APC residues were over 225€/tonne residue; and comprised 112.5€/tonne treatment costs for solidifying the APC residues in concrete and 112.5€/tonne for landfill/waste tax charges. Transport costs were site specific and were excluded from the above estimate.

9.2 Processing Costs of Residue Recovery and Re-Use Applications

One of the key issues for utilisation is the relative cost of disposal versus utilisation. Estimates of costs associated with utilisation of MSW ash residues are considered to be very site specific because of varied requirements for permitting, testing, transportation and cost offsets through reduction in disposal and natural materials costs. In general, information on cost estimates for re-use applications is limited. Table 9.2 summarises cost breakdowns supplied by the EfW operators who responded to the study.

In general, cost estimates for utilising bottom ash in civil engineering applications (with little or no pre-treatment requirements) are low, typically 6€ to 18€ per tonne of residue. In France, for example, costs for utilisation of weathered or untreated bottom ash in road construction applications was typically 12€ to 18€ per tonne. This compared with 7.5€ to 52.5€ per tonne for disposal operations. Similarly, disposal costs for bottom ash in the UK were around 24€ per tonne whilst costs for using untreated bottom ash in concrete block manufacture, as a coated material component and road construction applications were quoted to be around 9€ per tonne. Cost estimates for separation and recycling of the ferrous fraction to the metallurgic industry were typically 5€ to 15€ per tonne of residue.

Re-use techniques, which involve melting or thermal treatment, incur high capital, O&M, fuel and reagent costs. For example, in Japan, cost estimates for utilisation of bottom and fly ash slag in road construction, aggregate for concrete and interlocking block applications ranged from 99€ to 147€ per tonne of residue depending of the smelting technique employed. However, in this case, treatment costs compared favourably with estimated disposal costs of 180€ per tonne for the untreated residue.

Country	Re-Use Application	Cost Breakdown, € per tonne of residue*					Total
		Capital	O&M	Fuel	Reagents	Others	
Austria	Smelting (iron).	10.5					>10
Canada	Smelting (iron).						5
France	Road (sub-base).						12-18
Japan	Road construction, aggregate for concrete, interlocking block: *by plasma smelting*.		60	6	33		99**
	Road construction, aggregate for concrete, interlocking block: *by burner smelting*.		60	64.5	22.5		147**
Norway	Road (sub-base).	2.25				3.75	6
Spain	Road sub-base .						11.25
UK	Concrete block manufacture, bulk fill/sub-base, coated material component.						9

**Bottom Ash from mass burn EfW facilities. ** = excluding power and capital cost repayments. O&M = Operations and Maintenance.*

Table 9.2 Costs of MSW Bottom Ash Recovery and Re-use

10 INCENTIVES AND BARRIERS FOR RESIDUE UTILISATION

10.1 Incentives for Residue Utilisation

The treatment of MSW in EfW facilities is a widespread practice with a trend towards increased growth in the majority of IEA Member countries. Although amounts of ash residue generated are small by comparison to ash residue streams generated from firing of coal in utility and industrial boilers, MSW ash residues are considered to have the potential to more significantly impact environmental quality. The costs incurred for disposing of the waste ash residues in landfill sites represents a significant component of the overall operating costs of an EfW facility. The ability to create from ash residues value-added products that conform to regulatory requirements for management and use is an attractive option to generators of ash residue.

Two of the main constraints to the development of re-use options for waste ash residues are their product variability and their potential to have a harmful impact on the environment. A range of treatment processes have been developed which ensure that the ash products are environmentally benign. As awareness of the need to pre-treat residues increases, the key to utilisation is the relative cost of disposal versus utilisation. If landfill prices (and taxes where levied) rise significantly, alternative outlets will be sought actively.

Responses from the study EfW operators on incentive schemes and marketing strategies for the distribution and sale of usable MSW combustion residues are summarised in Table 10.1.

Country	Description
Canada	• Key incentive is the reduction in transport costs. • Assists in attaining MSW reduction goal of 50% by year 2000. • Market development.
France	• Legislation: waste has to be recovered or valorised as often as possible. • Publication of a regional guide about use of bottom ash in civil engineering. • Publication of a national information document by the Ministry of Equipment.
Japan	• Development of new residue utilisation. • PR to local governments to adopt these products from residue. • Development of commercial circulation routes of residue.
Norway	• *Bottom Ash*: Governmental tax approx. 45€/tonne if not utilised.
Sweden	• Improvement of technique for sorting out metallics to improve purity. • Efforts to convince regulatory institutions to allow bottom ash for civil engineering by providing analyses of material.
UK	• Demonstration trials for use and practices (road built from cement bound ash base and tarmacadam surface using only bottom ash as the aggregate). • EWA/WRC characterisation standard. • Low price, consistent quality and good availability.

Table 10.1 Incentive Schemes and Marketing Strategies for the Distribution and Sale of Usable Combustion Residues

The main incentives were summarised as:

Economics

One of the key issues for utilisation is the relative cost of disposal versus utilisation. Fiscal incentives for ash utilisation practised, involve implementation of taxes if the ash residues are not utilised and are disposed of at landfill sites. The waste or landfill taxes can be *cost covering charges* where the revenues are used either to pay for waste disposal services or to finance recycling services[38]. Or, they can be *incentive taxes* levied to change environmentally damaging behaviour. Revenues are often used to further encourage behavioural change[15]. The third way that a waste tax can be used is as *a fiscal environmental tax*, whereby surplus revenues from the tax can be used to finance budget deficits or shift taxes from labour to resources. If costs for disposal of the ash residues increase significantly, alternative outlets (such as re-use applications) will be sought actively. This is particularly applicable to countries were disposal costs are relatively low.

Market Development

In order to increase the amount of MSW ash residues utilised in various applications, it is important to gain market acceptance of MSW ash residues and promote its use as a predictable commodity. Successful marketing and use of the product can be achieved through satisfying and demonstrating to both the regulatory bodies and customers that products derived from MSW ash residues perform well in contemplated applications and that there is no risk of harm to human health or the environment. In the Netherlands an important factor in the market acceptance of bottom ash was that public authorities have acted as pioneers in its use. To promote the utilisation of MSW ash residues, regional and national documents on the use of bottom ash in various applications are being developed in many IEA/ISWA member countries. In the UK, for example, a protocol for characterisation and routine testing of MSW ash has been developed. There is also an exchange of information on the uses of bottom ash. In many countries, active development of new applications for residue re-use is being undertaken which will help to expand the capacity of the market for MSW ash residue utilisation. This has involved trial and demonstration schemes for re-use applications, and schemes for improving treatment techniques.

Specification Standards

The contamination and product variability issues are serious disincentives to the development of utilisation schemes for ash residues from MSW treatment facilities. To promote the idea that MSW ash residues can be a predictable and environmentally sound commodity, requirements must be developed for the use of ash residue products in contemplated applications. These requirements for good performance should be based on (i) the properties of the ash residues (e.g. chemical and physical characteristics, and standard engineering criteria) and (ii) the potential for environmental impact during product application lifetime. In many IEA/ISWA member countries, regulations and specification standards for the more common utilisation practices (such as in road construction applications) are already in place to address these issues and high standard upgrading techniques have been applied in order to obtain a consistent construction material which meets the physical and environmental performance requirements demanded by the market. These guidelines and regulations have been shown to influence civil engineering decision makers to accept MSW ash in place of sand and gravels. However, specification standards for the use of MSW ash residues in newer applications are required to guarantee environmental quality and the physical/chemical characteristics of the ash residues.

10.2 Barriers to Residue Utilisation

The principal constraints to the development of viable utilisation options are the release of contaminants through leaching or dust emission, the amount of processing required and the quality control of the residues. Specific barriers identified by the EfW operators who responded to this study are listed in Table 10.2 and are summarised below as properties of the ash residues; regulations governing residue re-use; lack of knowledge of end-use markets; and economic factors.

Country	Description
Austria	(i) Very strict national regulations for combustor residue re-use; and (ii) Natural minerals at lower costs and better quality available.
Belgium	Due to the lack of incentives no strong efforts are made for development. The law and the regulations are not available for re-use of combustor residues.
Canada	*Bottom Ash:*(i) Reluctance of municipalities/contractors to use a 'waste' residue in road construction; (ii) Variability in product specifications; (iii) Maximum ratio of bottom ash that can be used is 70% . *Treated APC Residues*: Reluctance exists on using treated material that was once a special waste.
France	(i) Lack of information about long term behaviour; (ii) Low cost of natural materials in some regions, cheaper than bottom ash and low cost of landfilling; (iii) Fear of associations.
Hungary	Hungarian regulations and waste categorisation.
Japan	(i) Perceived public option that re-use products are inferior quality; (ii) Stable demand is difficult to secure; (iii) Commercial circulation system of re-use is not established; (iv) Manufacturing cost of slag is very high compared with natural mine resources.
Netherlands	(i) Different specifications for the treatment of residues and re-use applications; and (ii) Economic viability of treating ash residues for re-use applications.
Norway	(i) Cheap raw materials; (ii) Cheap competitive recycled materials; (iii) Potential users of the material are sceptical regarding environmental impacts.
Spain	(i) Public perception/poor image of waste combustion processes; (ii) Lack of legal regulations; (iii) Low cost of raw materials and landfill taxes.
Sweden	(i) Lack of standards for combustion residue control and no national regulations mean variations in county administrative board ruling (ii) Bottom ash is currently not allowed for civil engineering applications (iii) Difficulties in achieving pure metallic fraction from bottom ash.
UK	*End-User Concern:* (i) Ash properties - variability, different to PFA and potential problems from leachates (now produced product data sheet); and (ii) Potential users reluctance to take a technical risk; (iii) May be seen as inferior to products using natural aggregates; and (iv) Transport costs limit markets. *Regulatory Constraints:* (i) Agreement with EA concerning classification of bottom ash; and (ii) Potential and actual opposition from EA for ash storage and processing schemes as well as use.

EA = Environment Agency

Table 10.2 Barriers that Hinder Development of Residue Utilisation

Ash Residue Characteristics

Serious disincentives to the development of ash re-use schemes for waste combustion residues are the presence of contaminants and residue/product variability issues. Potential end users of waste ash residues are sceptical regarding environmental impacts resulting from leaching of metals and salts from the ash residues and the lack of information on their long term behaviour. The presence of these contaminants can also have an adverse effect on product performance. For example, alkali metals and chlorides in ash residues need to be limited for concrete and cement applications since they give rise to loss of strength and risk of corrosion in reinforcement bars. The variability of the chemical and physical characteristics of the ash residues make it difficult gain acceptance as a predictable commodity and potential end users are reluctant to take technical risks. There is a perceived public opinion that re-use products from waste ash residues are of inferior quality, which has an adverse effect on market acceptance of the ash residue.

Regulations Governing Residue Re-Use

In many IEA/ISWA member countries, requirements (regulations and specification standards) for the use of ash residues in various applications either do not exist, vary depending on the local authorities or are considered to be restrictive. The lack of consistent and appropriate regulations and specification standards for residue re-use applications will have an adverse effect on the market acceptance of MSW ash residues. Successful marketing and use of the product can best be achieved through satisfying both the regulatory bodies and customers that MSW products meet the performance requirements demanded by the market and that there is no risk of harm to human health or the environment. For example, experience has shown that market acceptance of these residues has been gained in countries where requirements for the more common utilisation practices (such as in road construction applications) are already in place[36].

Knowledge of End-Use Markets

In certain IEA/ISWA member countries, principal constraints to the development of viable utilisation options, is the lack of knowledge of re-use applications and end-use markets, other than for bottom ash in the more common utilisation practices. To promote the concept that MSW ash residues can be a predictable commodity and to increase ash utilisation, active development of new applications and markets is required. Potential end users, marketing bodies and operators of EfW treatment plants should be encouraged to take a proactive role in development projects designed to seek sustainable approaches for the management of residue streams. This should involve trial and demonstration projects for re-use applications, development of regulations and specification standard for the application, development of commercial markets for re-use applications and schemes for improving treatment techniques. There is also a need for an exchange of information and experience on the uses and potential markets for MSW ash residues between countries, such as the Netherlands, who encourage high levels of ash utilisation and others were re-use applications are not established.

Economic Factors

One of the key issues for utilisation of MSW ash residues is the relative cost of disposal versus utilisation. If costs for disposal of the residues increase significantly, alternative outlets will be actively sought. The main economic barriers for ash residue utilisation identified from the response of the study EfW plants are (i) natural minerals (and other recycled materials) are available at lower costs and better quality; (ii) treatment/manufacturing costs are high compared with natural resources; (iii) transport costs limit markets to nearby locations; and (iv) the relatively low cost of landfilling in certain countries. Many of these issues are site specific, and the economic viability of MSW ash residue utilisation will be dependent on the on the EfW treatment plant location.

11 FOCUS OF R&D ACTIVITIES

High landfill charges and limits on organic materials to landfill are prompting research into the benefits and consequences of alternative approaches for the management of ash residues from EfW facilities. Waste ash residues are considered to have the potential to have a harmful impact on environmental quality and consequently, a large amount of R&D is being conducted concerning the management and handling of these waste ash residues. R&D activities financed by the state and the European Commission are important since they benefit everyone and can also concern areas that are not profitable in the short term. Private companies, municipalities, and municipally owned companies also pursue their own development programmes. The main areas of research and development (R&D) activities identified by the study EfW operators are given in Table 11.1 and can be summarised in three main activity areas; waste ash characteristics, waste ash treatment processes, re-use applications.

Waste Ash Characteristics

The properties of ash residues from EfW treatment facilities vary considerably depending on the waste source and combustion process. In addition, the presence of contaminants in the ash can lead to poor environmental performance and may also have an adverse effect on the product performance. Knowledge of the ash characteristics is essential to determine appropriate management practices and utilisation opportunities. R&D being carried out in this activity involves investigation of key properties of the ash residues important for re-use applications and the potential for environmental impact during the product lifetime. For example, in countries such as the UK, Sweden, Spain and Japan, waste ash residues are being characterised for specific re-use applications, such as in the manufacture of brick and concrete based products, land reclamation and road construction. Ways of improving the characteristics of ash residues for re-use applications are also being investigated in Canada and the Netherlands. In France, the long term leaching and stabilisation characteristics of waste ash residues are being studied to establish their environmental impact in re-use applications.

Waste Ash Treatment Processes

Present trends and data indicate a preference for use of bottom ash in commercial applications. Difficulties arise with use of other ash residue fractions (fly ash and APC residues) due to poor performance or potential concerns for mobilisation of elements incorporated in products. Various techniques have been developed aimed at improving MSW residue properties to allow beneficial use or to fix the contaminants in the residue matrix, thus leading to less stringent disposal regimes. A wide range of treatment processes have been developed for disposal, recovery and re-use operations. These range from simple techniques such as screening, weathering and removal of specific materials to more sophisticated procedures involving chemical, thermal or solidification/stabilisation treatment. The suitability of a treatment technique is dependent of the waste characteristics, the EfW combustion process and the intended end management practice. The implementation of the various techniques depends on the treatment costs and beneficial application of the end products. In many IEA/ISWA member countries, R&D is being undertaken to develop improved techniques for treating MSW ash residues to allow beneficial use in re-use applications. For example, research projects in Austria, Norway, France, Hungary, Spain and the UK, are aimed at improving techniques for stabilisation/solidification of waste ash residues for disposal and re-use applications. The main focus of this work has been to develop cost effective methods for treating fly ash to allow beneficial use or incur less stringent disposal regimes. Efforts are also being made to improve techniques for metal recovery to increase the quality and reduce variability of product.

Country	Activity	Description
Austria	On-line monitoring. Solidification	On-line monitoring of combustion process, Technical University of Innsbruck, 10/97 to 12/98. Improvement of residue solidification, Technical University of Innsbruck, 10/97 to 12/98.
Canada	Product quality. Potential APC Residue uses.	*Bottom Ash*: "Development of a process to increase quality and reduce variability of product", Blue Sky Mines Ltd. Method is a proprietary mineral aggregate processing technology. Funded through revenues from recovery and sale of metal. *Treated APC Residues*: Plan to perform pilot trials of viable technologies/uses.
France	Bottom ash study. Fly ash metal recovery.	Studies on long term leaching and stabilisation. Vitrification, with in some cases, recovery of metals.
Hungary	Fly ash treatment.	Physical and chemical stabilisation and immobilisation of fly ash.
Japan	Bottom ash uses.	(i) aggregate material for interlocking block, concrete brick and face wall material; (ii) civil works materials for sub-base course material, base course material and asphalt aggregate materials.
Nether-lands	Residue quality.	Ways of improving the quality of ash residues.
Norway	Bottom ash uses.	Stabilise bottom ash by use of bitumen.
Spain	Bottom ash uses. Treatments.	Characterisation of materials and leachates to be used for substrates, cement clinker, aggregate in roads, embankment and pavements. Fly ash treatments and bottom ash ageing.
Sweden	Ash utilisation. Standard.	Utilisation of ash, including fabric filter residues and bottom ash produced from various types of wastes. Development of analytical standards.
UK	Ash uses. Fly ash treatment. Added value uses. Standard.	Characterisation of ash residues and identification of potential uses in construction (brickworks, aerated concrete blocks, other concrete based products), land reclamation (from sea) or for use as road foundation material. Process being investigated to treat fly ash to encapsulate or otherwise fix heavy metals so that product may be used. 'Added value' products such as coated asphalt and concrete blocks. Adding value to ash by removing free lime. Trying to achieve a standard specification for ash based products.

APC = Air Pollution Control residues

Table 11.1 Research and Development Activities

Re-Use Applications

Efforts to utilise MSW ash residues in various applications are being carried out world-wide. Interest in utilisation principally is motivated by economic factors such as increasing disposal costs and the ability to create from ash residues value-added products. To date, effort has concentrated on the re-utilisation of bottom ash residue, where this material can be used as an alternative aggregate material for civil engineering applications, such as base and sub-base for roadways. Practical uses for fly ash and APC residues are reported to be limited, due to the presence of leachable contaminants and their fine particle size. In addition, because of the variability of MSW ash residue properties, the suitability for various utilisation applications will be specific for a particular ash/EfW treatment plant. Current R&D projects include a study being carried out in Japan, to establish the potential for utilising waste ash residues in applications, such as in road construction, brick and concrete based products manufacture. In the UK, the potential for using waste ash residues in added value applications, such as coated asphalt is being investigated and in Canada, pilot plant scale demonstration trials are being carried on viable re-use applications for APC residues.

Legislation

In order to promote the idea that MSW ash residues can be a predictable commodity, regulations and specification standards are required for untreated/treated MSW ash residues, and for the use of ash residue products in contemplated applications. These requirements for good performance should be based on (i) the properties of the ash residues (including standard engineering criteria) and (ii) the potential for environmental impact during product application lifetime. Regulations and specification standards can be used to address these issues. In countries such as Sweden and the UK, analytical and specification standards are being developed for MSW ash residues/products.

12 CONCLUSIONS, MAIN ISSUES AND RECOMMENDATIONS

12.1 Current Practices for Management of MSW

- The majority of IEA/ISWA member countries are introducing stricter legislation and making considerable efforts to reduce the amounts of waste being landfilled through recycling and treatment in Energy from Waste (EfW) facilities.

- The most widely deployed EfW processes for treating MSW are mass burn plant. An alternative approach is to sort the household waste and burn the combustible material in a fluidised bed combustor. A third category under development is based on pyrolysis of the waste and combustion of the fuel gas. There is no unique answer as to which EfW combustion technology is better. Each situation has to be considered on its own merits, taking into consideration related institutional, environmental and economic issues.

- The main component of the solid residues is bottom ash, which, for a mass burn plant, represents around 30% by weight of the original waste. Fly ash and APC residues are often combined prior to disposal/utilisation and represent around 4% by weight of the original waste.

12.2 MSW Ash Residue Characteristics and Categorisation

- Different waste sources and combustion processes generate residues with significantly different chemical and physical characteristics. Knowledge of the waste ash residue characteristics is essential to determine appropriate management practices, utilisation opportunities and to ensure minimal environmental impact.

- Bottom ash represents the residuals from the combustion of MSW and is an inorganic, sterile material with the consistency of sandy gravel, containing about 10 to 15% of ferrous metals. In mass burn facilities, after the ash is discharged from the grate, it is quenched in water before metals are separated by magnets for recycling. In FBC facilities, bottom ash is not quenched and contains a high proportion of sand particles from the fluidised sand bed.

- Fly ash and APC residues arise from the particulate removal systems during cleaning of the flue gas. These residues consist of fine particulates (that have been entrained in the gas stream) and the reagents/products (such as lime or activated carbon and salts) removed from the flue gas stream.

- The main components in all waste ash residue streams were the inorganic salts and oxides of silicon, aluminium, calcium and iron. Fly ash and APC residues can also contain substantial levels of chlorine and organic carbon. These, together with sodium, potassium, magnesium and sulphate, were shown to be highly soluble in aqueous media.

- Metals were shown to be present in all ash residue fractions, and the EfW operation can have a pronounced impact upon metal speciation and the report of metal species to various ash residue fractions. Compared bottom ash, fly ash and APC residues characteristically contain significantly higher concentrations (though not always the largest total amounts) of potentially leachable fractions of these metals. Metals in bottom ash streams are generally considered to be less mobile.

- Trace organics of potential human health concern, such as PCDFs, PCDDs, PAHs and PCBs, have been quantified in MSW bottom ash from mass burn plants. Although most well operated

MSW EfW facilities are able to achieve low levels of these compounds in bottom ash streams, fly ash and APC residues can contain higher levels of PCDDs and PCDFs.

- In the majority of IEA/ISWA member countries, bottom ash from mass burn MSW treatment facilities is classified as non-special waste. Fly ash and APC residues are generally categorised as special waste due to the presence of higher levels of leachable metals.

12.3 Current Residue Treatment Practices

- Various techniques have been developed aimed at improving MSW ash residue properties to allow beneficial use or to fix the contaminants in the residue matrix, thus leading to less stringent disposal regimes and lower environmental impact.

- For bottom ash, pre-treatment techniques to screen oversized components, to remove ferrous metal and to allow weathering of the material are recognised low cost procedures for improving the chemical integrity and structural durability of the material prior to disposal or re-use applications. There is little evidence of widespread use of treatment techniques, such as solidification/stabilisation of the bottom ash (except for use as compacted granular base), due to additional processing requirements and higher processing costs.

- Pre-treatment of the fly ash and APC residues (using processes such as solidification /stabilisation) prior to landfilling is becoming a recognised economically viable management option.

- The suitability of a treatment technique is dependent of the waste characteristics, the EfW combustion process and the intended end management practice. The implementation of the various techniques also depends on the treatment costs and beneficial application of the end products.

12.4 Current Practices for Utilisation of Ash Residues

- Efforts to utilise ash residues in various applications are carried out world-wide. Interest in utilisation principally is motivated by the potential for (i) extending existing ash landfill capacity (and thus reducing disposal costs) and (ii) the ability to create from ash residues value-added products.

- The principal constraints to the development of viable utilisation options are the potential for the release of contaminants through leaching or dust emission, the amount of processing required and the quality control (i.e. chemical and physical property variability) of the residues.

- To promote the utilisation of MSW ash residues many countries have developed regulations and specification standards for (i) untreated/treated ash residues, and (ii) the use of ash residue products in contemplated applications.

- Bottom ash from mass burn EfW treatment facilities is considered to have the greatest potential for utilisation because it typically has the lowest levels of contaminants, has physical properties similar to lightweight aggregates and represents over 80 weight percent of the total residues generated. However, the amount of bottom ash which is utilised throughout the IEA/ISWA member countries, varies significantly from 0% to almost 100%.

- To date, the main applications for bottom ash are as an aggregate replacement in asphalt used for binder or base courses for road/pavement construction. Other potential applications for

MSW bottom ash include embankment fill; aggregate for concrete building blocks; daily cover material for landfills; and noise or wind barriers.

- Utilisation options for fly ash and APC residues are limited due to their fine particle size and the presence of relatively high levels of contaminants. However, the potential for use as fillers for asphalt; as a filler/pozzolanic additive in concrete; and as a grout in coal mines have been demonstrated.

12.5 Current Disposal Practices for Ash Residues

- Disposal practices for ash residues from EfW treatment facilities vary widely across the world. Monofill represents the most common method of bottom ash disposal in Europe and Canada, although co-disposal of MSW ash residues with other wastes, including MSW, does occur. In the majority of countries, bottom ash passes the national landfill regulations and does not require pre-treatment.

- Stricter disposal regulations exist for fly ash and APC residues due their finer particle size and the presence of higher concentrations of leachable/toxic metals. In certain countries, disposal of untreated special (hazardous) wastes (e.g. fly ash and APC residues) is being restricted to mono-filling at fully contained landfills situated on non-aquifiers. Whilst in others, landfilling of untreated fly ash and/or APC residues has been prohibited. These residues require pre-treatment, such as solidification and stabilisation, to improve their environmental quality prior to disposal.

12.6 Economics

- Disposal costs for ash residues from EfW facilities vary significantly throughout the IEA and ISWA member countries. The main cost variant for bottom ash disposal is the waste/landfill tax, which is dependent on national/regional tax legislation and categorisation of the ash residue stream as special or non-special waste.

- Disposal costs for fly ash and APC residues were significantly higher. This was mainly attributable to additional treatment process costs or higher landfill taxes. In countries employing high disposal charges, the cost benefits incurred from down grading of the waste disposal categorisation for treated APC residues, from special to non-special waste, can outweigh the treatment costs.

- One of the key issues for utilisation is the relative cost of disposal versus utilisation. Costs for utilising bottom ash (mainly in an untreated form) in road construction and civil engineering applications were generally lower than those incurred for disposal to landfill.

- Re-use techniques, which involve melting or thermal treatment, incur significantly higher treatment costs and may have economic advantages in countries with high disposal charges.

12.7 Incentives for Ash Utilisation

- One of the key issues for utilisation of MSW ash residues is the relative cost of disposal versus utilisation. Fiscal incentives for ash utilisation being practised in many IEA/ISWA member countries, involve implementation of taxes if the ash residues are not utilised and are disposed of at landfill sites.

- To develop viable ash utilisation options, it is important to gain market acceptance of MSW ash residues and to promote its use as a predictable commodity. In many countries, successful marketing and use of the product is being achieved through satisfying and demonstrating to both the regulatory bodies and customers that products derived from MSW ash residues perform well in contemplated applications and that there is no risk of harm to human health or the environment.

- Regulation and specification standards are being developed for the use of MSW ash residue products in contemplated applications, to promote the idea that MSW ash residues can be a predictable and environmentally sound commodity.

12.8 Barriers for Ash Utilisation

- The presence of contaminants and residue/product variability issues were identified as being important disincentives to the development of ash re-use schemes for waste combustion residues. There is also a perceived public opinion that re-use products from waste ash residues are of inferior quality.

- In many IEA/ISWA member countries, an important barrier that hinders the development of residue utilisation is the lack of consistent and appropriate regulations and specification standards for residue re-use applications.

- Another constraint to the development of viable utilisation options, for certain countries, is attributable to the lack of knowledge of viable re-use applications and end-use markets.

- A key issue for utilisation of MSW ash residues is the relative cost of disposal versus utilisation. The main economic barriers for ash residue utilisation identified were the lower costs of natural minerals compared to ash residues, higher treatment/manufacturing costs, transport costs limiting markets to nearby locations and in certain countries the relatively low cost of landfill.

12.9 Current R&D Activities

- R&D activities being carried out in IEA/ISWA member counties, include investigations of the key MSW ash residue properties important for re-use applications; development of improved techniques for treating ash residues; demonstration of the potential for using ash residues in viable re-use applications; and development of specification standards for MSW ash residues and their products.

12.10 Recommendations

- The current trend for increased growth of MSW EfW treatment facilities will result in increased amounts of ash residues being generated. Efforts should be made to reduce the amount of MSW ash residues for disposal, by considering alternative utilisation options that are economically and environmentally attractive.

- Ways of improving the quality and reducing the variability of MSW ash residues are required to encourage the perception that ash residues are a valuable product rather than a waste stream. Procedures could include screening/selection of the raw waste input to the EfW combustion plant and/or application of treatment techniques to improve the ash residue properties. In many countries, treatment techniques to screen oversized components, to remove ferrous metal and to allow weathering of the material are recognised procedures for improving the environmental performance and ash properties to allow beneficial use. Other treatment techniques being used or investigated, are based on thermal, chemical and solidification/stabilisation processes. The suitability and implementation of the available techniques is dependent on the treatment costs, the benefits to end-use application and the properties of the ash residue. Further information on the benefits of the various treatment practices for specific ash residues is required, in terms of improved ash properties for re-use applications, environmental performance and economic viability.

- Successful marketing and use of MSW ash residues can best be achieved through satisfying both the regulatory bodies and customers that MSW products meet the performance requirements demanded by the market, and that there is no risk of harm to human health or the environment. In order to promote the idea that MSW ash residues can be a predictable commodity, it is important to adopt regulations and specification standards for use of ash residue products in all contemplated applications. These requirements for good performance should be based on (i) the properties of the ash residues and products (including standard engineering criteria) and (ii) the potential for environmental impact during product application lifetime.

- Bottom ash is considered to have the greatest potential for utilisation and, to date, the use of this material as an alternative aggregate material in civil engineering applications is fairly well established in many IEA/ISWA member countries. Efforts should be made (for example, through R&D studies) to further investigate the potential for using bottom ash in added value and other applications. This work should involve or lead to further trials at demonstration scale to provide appropriate evidence of the benefits, in terms of product performance, economic viability and environmental impact, and how best they can be achieved.

- Operators of EfW treatment plants, marketing bodies and potential end users should be encouraged to take a proactive role in research and development projects designed to seek sustainable approaches for the management of residue streams. This should also involve trial and demonstration schemes for improved treatment techniques and viable re-use applications to ensure that key issues for the utilisation of MSW ash residues are addressed.

- Practical uses for fly ash and APC residues are limited and stricter disposal regulations exist due to the presence of contaminants and their fine particle size. Many countries are now required to treat these residues, to improve their environmental quality, prior to disposal. Most of the practices currently adopted involve relatively expensive stabilisation /solidification techniques. Efforts should be made (for example through R&D studies) to develop more cost-effective methods for treating fly ash and APC residues to allow beneficial use or to incur less stringent disposal regimes.

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14 REFERENCES

1 International Ash Working Group (IAWG), 'An International Perspective on Characterisation and Management of Residues from MSW Combustion', December 1994.

2 Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. Dritte Allgemeine Verwaltungsvorschrift zum Abfallgesetz (TA Siedlungsabfall) Technische Anleitung zur Verwertung, Behandlung und sonstigen Entsorgung von Siedlungsabfällen vom 14. Mai 1993, Bundesanzeiger Jahrgang 45, Nr. 99a, 1993.

3 AOO (Dutch Waste Planning Council), "Ten Year Programme Waste, 1995-2005", 1995.

4 'DG XI Guide to the Approximation of EU Environmental Legislation', http://eurpoa.eu.int/comm/dg11/guide/part2c.htm.

5 IEA Bioenergy: Task 23, N M Patel, AEA Technology plc, Harwell, Didcot, Oxfordshire, OX11 0RA.

6 Russotto N, The European Waste Policy in Action, EEWC, London, 3 March 1999.

7 Andersson C, 'Waste to Energy in Sweden. Högdalen a Successful Example', paper presented at the ISWA Seminar, 'Waste to Energy: A Step Towards the Renewable Energy', Brescia, 7 May 1998.

8 An Introduction to Household Management, Resource Recovery Forum, ETSU for the UK DTI, Harwell, Didcot, Oxfordshire, UK, March 1998.

9 'The Thermal Destruction of Waste', IEA Greenhouse Gas R&D Programme, Report Number PH2/18, November 1998.

10 Environmental Protection Act 1990: Part II Special Waste Regulations 1996 (Circular WO21/96 (Welsh Office)), HMSO, London.

11 'Ash Handling from Waste Combustion', Technical Brief from the World Resource Foundation, Kent, UK, http://www.wrfound.org.uk/wrftbash.html, 1999.

12 Greill R, Stammbach M R, "Applications of the RCP-System Based on RCP-Derivatives: The Von Roll 18 MW Standard Plant", paper presented at Waste to Energy – The Latest Technical Development, Malmö Börshus, Skeppsbron 2, Malmö, Sweden, September 30 – October 1 1999.

13 Andersson C, 'Waste to Energy in Sweden. Högdalen a Successful Example', paper presented at the ISWA Seminar, 'Waste to Energy: A Step Towards the Renewable Energy', Brescia, 7 May 1998.

14 DETR, 'The Use of Incinerator Bottom Ash as Aggregate', http://www.planning.detr.gov.uk/aas /index.htm.

15 Chandler A J, Eighmy T T, Hartlen J, Hjelmar O, Kosson D S, Sawell S E, van der Sloot H A and Vehlow J, 'Municipal Solid Waste Incinerator Residues', The International Ash Working Group, Studies in Environmental Science 67, Elsevier, ISBN 0-444-82563-0, 1997.

16 Practical Effects of UK and North American Recycling Programmes, a report presented to the Energy from Waste Foundation by MEL Research Limited, Aston Science Park, Birmingham, UK, Report 98/015, April 1999.

17 Thurtle G, 'Incineration Directive begins to take Shape', Material Recycling Week, Friday July 1999.

18 NREL Technology Brief, Colorado 80401-33933, National Renewable Energy Laboratory, NREL/BR-430-21437, Dec 1996.

19 Ruth L A, 'Energy from Municipal Solid Waste: a Comparison with Coal Combustion Technology', Progress in Energy and combustion Science, **24** (6), 545-564,1998.

20 DG XVII, 'Energy from Co-Firing of Coal and Waste Derived Fuel: Slough Trading Estate Power Plant', Brussels, Belgium, European Commission Directorate General for Energy (DG XVII), October 1998.

21 Sundermann B, Rubach T and Rensch H P, 'Feasibility Study on the Co-Combustion of Coal/Biomass/Sewage sludge and Municiple Solid Waste for Plants with 5 and 20 MW Thermal Power using Fluidised bed Technology', In *Combined Combustion of Biomass/Sewage Sludge and Coal, APAS Clean Coal Technology Programme*, APAS Contract Coal-CT92-0002, Volume II, Final Report, 1992-1994.

22 Gerhardt T, Cenni R, Spliethoff H and hein K R G, 'Combustion Behaviour of Coal-Waste flames in Pulverised Fuel Fired Systems', paper presented to: *22nd International Conference on Coal Utilisation and Fuel Systems*, Clearwater, FL, USA, March 1997.

23 Krause H H, Vaughan D A, Cover P W, Boyd W K and Olexsey R A, 'Corrosion and Deposits from combustion of Solid Wastes. Part VI: Processed Refuse as a Supplementary Fuel in a Stoker-Fired Boiler', *Transactions of the ASME: Journal of Engineering for Power*, **101**, 592-597, October 1979.

24 Ohlsson O O, 'Results of Performance and emission Testing when Co-Firing Blends of RDF/Coal in a 440 MWe Cyclone Fired Combustor', In: *Alternate Fuels IV Conference*, New Orleans, LA, USA, 8-9 February, Burke V A, USA, Council of Industrial Boiler Owners, 39-52, 1994.

25 Bemtgen J M, Hein KRG and Minchenmer A J, 'Combined Combustion of Biomass/Sewage Sludge and Coal, APAS Clean Coal Technology Programme', APAS Contract Coal-CT92-0002, Volume II, Final Report, 1992-1994.

26 US EPA Science Advisory Board, 'Leachability Phenomena - Recommendations and Rationale for Analysis of Contaminant Release', Environmental Engineering Committee, Washington DC, October 1991.

27 Lewin K, Blakey N C, Turrell J, Bradshaw K, Russell A, Harrison J, van de Sloot H and Collins R, 'Properties and Utilisation of MSW Combustion Residues', Contractor WRc plc, ETSU B/RR/00368/REP, 1996

28 Draft European Waste Compliance Test as proposed by the CEN Technical Committee 292 (Characterisation of Waste), Working Group 2 (Leaching Test Procedures), CEN 1994.

29 Special Wastes: A Technical Guidance Note on their Definition and Classification; Volume 1: Legislative Framework and Assessment Methodology, Draft for Consultation, Environment Agency, SEPS, May 1998.

30 Kosson D S, Clay B A, van der Sloot H A and Kosson T T, 'Utilisation Status, Issues and criteria Development for Municipal Combustor Residues in the United States', Environmental Aspects of Construction and Waste Materials, 1994.

31 Lyons M R, 'The WES-Phix® Ash Treatment Process', Manager, Ash Programs, Wheelabrator Environmental Systems Inc., 1995.

32 PRISM-WRF Tech Brief (Ash), http://www.wrfound.org.uk/wrftbash.html, July 1999.

33 'Burnaby Incinerator, http://www.gvrd.bc.ca/waste/bro/swincin.html, July 1999.

34 VIT, 'Waste Vitrification; Transformation of Waste Problems into Glass and Glass-Ceramic Products', http://www.vitrification.com/waste%20vitrification.htm, July 1999.

35 HI disposal Systems, 'Ash and Landfills', http:///www.hicompanies.com/hawkins_42.html, July 1999.

36 Born J G P, van Ruiten L H A M and van der Sloot H A , 'Treatment & Beneficial Use of MSWI Residues in the Netherlands', Publication by Novem, Netherlands Agency for Energy and Environment, 1997.

37 Kruszewska I, 'The Effectiveness of Taxes on Reducing Waste', First International NGO Skillshare on Clean Production: Background Reading Material, http://www.rec.org/poland/wpa/wastax.htm.