

**UN/ECE TASK FORCE on MANAGEMENT of BY-PRODUCTS and
RESIDUES containing HEAVY METALS AND POPs**

**Management of By-products/Residues Containing Heavy Metals and
Persistent Organic Pollutants from Waste Incineration**

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1 WASTE INCINERATION

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1.1 Introduction

Waste incineration can be defined as the thermal conversion processing of solid waste by chemical oxidation. The types of wastes range from solid household rubbish and infectious hospital waste through to toxic solid, liquid and gaseous chemical wastes. End products include hot incineration gases, composed primarily of nitrogen, carbon dioxide, water vapour and to a smaller extent of non-combustible residue (ash) and air pollutants (e.g. NO_x). Energy can be recovered by heat exchange from the hot incineration gases. Burning of solid waste can fulfill up to four distinctive objectives (Pera, 2000):

1. Volume reduction: volume reduction of about 90 %, weight reduction of about 70 %.
2. Stabilisation of waste: oxidation of organic input
3. Recovery of energy from waste
4. Sanitarization of waste: destruction of pathogens

Waste incineration is not a means to make waste disappear. It does entail emissions into air as well as water and soil. The generated solid residues are the topic of this Task Force. Unlike other industrial processes discussed in this platform, waste incineration is not a production process, and is therefore not generating by-products, only residues. Residues that are isolated from e.g. flue gas, are concentrated in another place and form (e.g. air pollution control residues). Hence, there are generally two groups of residues that have to be taken into consideration: Residues generated in the actual incineration process and others generated in the flue gas cleaning procedure. Should waste incineration finally gain public acceptance, it will be necessary to find consistent regulations for both sorts of residues. In some countries waste incineration is seen as the best option for the treatment of waste, whereas in other countries it is seen very negative.

1.2 Properties of Waste

Besides the firing technique and the flue gas cleaning system, the composition of waste is of utmost importance for the quality and composition of the generated residues. Hence, the first step towards a reduction of incineration residues has to be made by analysing the input material and separation of certain components before the actual incineration. Hazardous material or material that could entail hazardous emissions should be subject to specific (pre-) treatment. Valuable material should be recovered or re-used. Some of these measures below have already been implemented, others have been suggested in literature:

- Separation of ferrous and non-ferrous metals (reduction of Al, Cu, Mo and Hg in residues)
- Separation of the fraction of diameters < 20 mm (reduction of Pb, Zn, Cu, Sb and Cd, in residues)
- Control the actual macro-composition of the refuse for targeted reduction of certain residues
- Product-related measures for targeted reduction of residues (e.g. batteries, lead bottle caps)
- Separate collection of electronic scrap, leather waste, plastics etc (reduction of Sb, Br, Pb, Cr, Cd, Cu, Ni, Hg and Zn)
- Optimisation of the collection of hazardous material
- Exclusion of specific sorts of waste for targeted reduction

Table 1: Origin of some environmentally problematic elements in solid residues:

Element	Origin in waste (examples)
Ammonia	Cleansing agents
Pb	Alloys, pigments, PE-stabilisers, Pb batteries, PVC
Cd	Ceramics, PVC-stabiliser, Ni/Cd-batteries, alloys, pigments
Cr	Leather-shoes and -clothing, metal plating, pigments
Cl	PVC, cleansing agents
F	Hobby-chemicals, clothing
Cu	Electronic scrap, wood preservative
Ni	Plating of Fe, batteries
Hg	Batteries, thermometers, amalgams
Zn	Pigments, paints, rubber products, inks, plastics, textiles
Sulphate	Cleansing agents

An unambiguous relationship has been derived between certain compounds in waste and their influence on the composition of the bottom ash. The allocation of HMs in the residues is influenced by several parameters such as their binding form, combustion temperature and chloride-content. The leaching properties, however, are strongly influenced by the mineralogical composition as well as the contents of reactive Ca, Na, K, Al and Fe. The presence of Si, Al and Ca leads to the formation of silicate-glasses at 1300-1400°C that have a high capacity to immobilise heavy metals. The separation of certain HMs from waste would therefore not always directly improve the results of the leaching tests.

1.3 General Process and Plant Description

The incineration process consists of four major phases generating different types of emissions:

- Drying phase: Increase of temperature leads to evaporation of water / moisture of the waste.
- Degasification phase: Further temperature increase transfers certain substances into the gas phase, sometimes entailing cracking processes (pyrolysis).
- Gasification phase: Carbon is converted into gaseous, combustible components.
- Incineration phase: The last step is the oxidation of combustible gases with air oxygen producing heat.

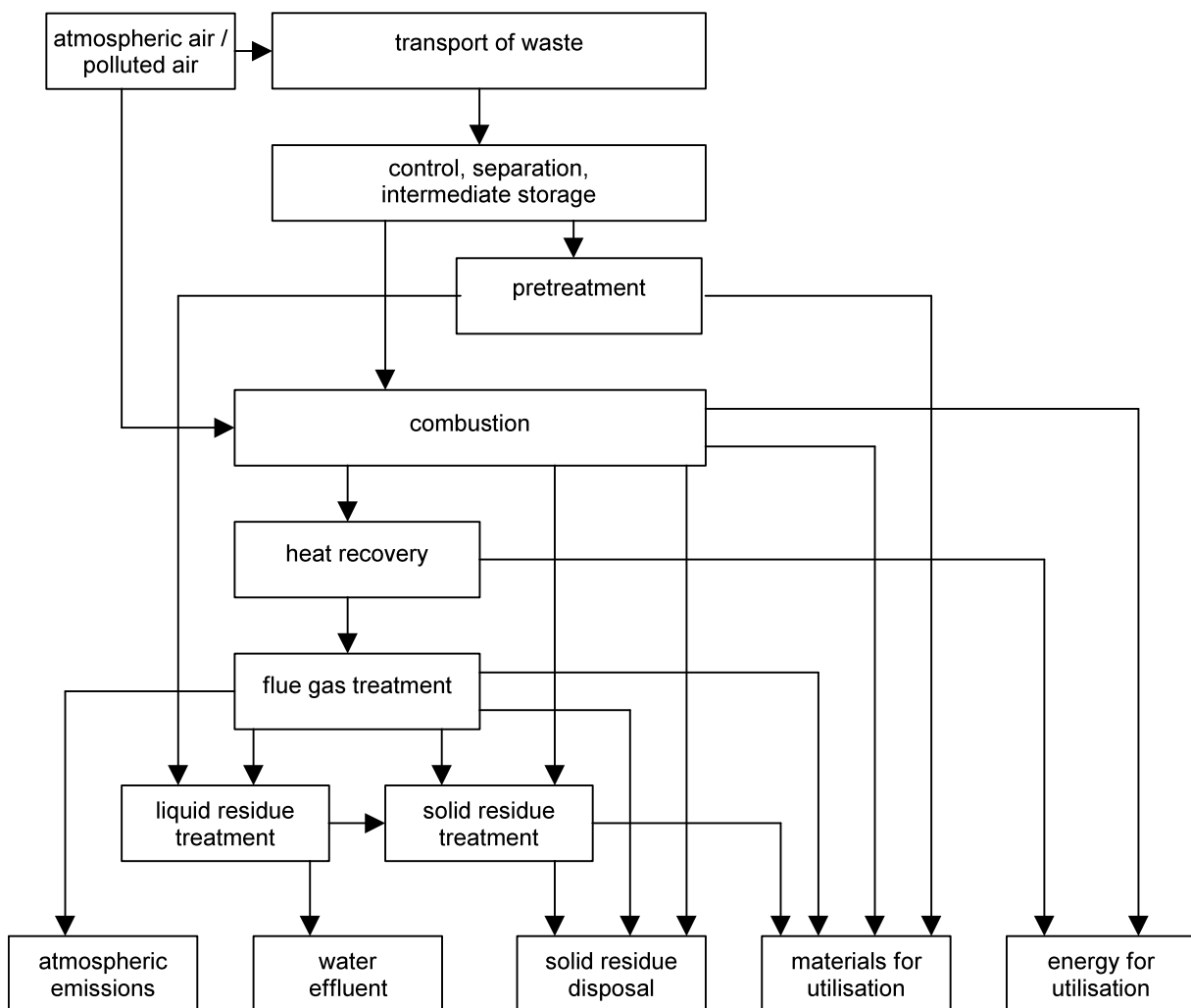


Figure 1: Overview of the various technical systems within a waste incineration facility

According to the state-of-the-art the major technical systems for the incineration of municipal and industrial waste are grate firing, rotary kilns with afterburner chamber and various fluidised bed reactors.

Table 2: Overview of Technical Systems and Typical Waste Input and Design Capacities

Type of Incinerator	Typical Waste Input
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Grate firing	Municipal garbage and similar commercial waste, sewage sludge ¹
Rotary kiln	Various solid, pasteous, liquid and mixed wastes, hazardous material
Fluidised bed	Sewage sludge, bark, wood chips, plastics, shredder residues

1.3.1 Grate firing

Mechanical grate firing is most commonly used for the incineration of household waste and to some extent for co-incineration of dried or de-watered sewage sludge. Also commercial waste similar to household waste and industrial waste, tires and - under certain conditions - medical waste can be combusted in grate firing installations.

Grate firing plants consist of a waste feeding device, a mechanical grate for transporting and poking the waste during the combustion phase, and a combustion chamber above the grate, through which the flue gases exit the combustion chamber, and where remaining gas and solid particulates are burned. The bottom ash can be discharged at the lower end of the inclined grate.

In order to guarantee the best possible degree of combustion under the prevailing conditions, the amount of air (oxygen) injected should exceed the stoichiometric requirements. An excess of oxygen in the combustion air raises the temperature in the combustion chamber and hence reduces the formation of PCDD/F by up to 90 % depending on the O₂-concentration (Bosch, 1999). In many cases combustion air is extracted from the waste reception pit to minimise smell. Primary air is blown into the combustion chamber from below the grate and through the waste feed. Secondary air and tertiary air (if required) is injected into the combustion chamber.

The thermal treatment of wastes aims at quantitative combustion, the performance of which is assessed on the basis of ignition losses of the various streams of solid residues and the composition of the flue gases. In modern incinerators the ignition losses of slag and ash range between 1 and 3 %. The most important criteria for complete combustion are temperature, residence time, turbulence in the combustion chamber and the contact between waste material and combustion air. The latter is guaranteed by grate systems equipped with devices to circulate and transport the waste material. The most frequently used grate systems are Forced-feed grate, Reversed-feed grate and Roller grate.

Depending on where the gases exit the combustion chamber, the grate firing systems can be subdivided into three groups: parallel, middle and reverse flow firing.

1.3.2 Rotary kiln with afterburner chamber

The rotary kiln with a subsequent combustion chamber is a most reliable plant for the thermal treatment of hazardous waste and can be used for the combustion of solid, liquid, pasteous and gaseous wastes. Accordingly there are different methods of feeding the kiln. Solid wastes are frequently introduced via sluice systems or chutes at the front or feeding wall. At the end of the chute, the waste fuel is fed into the rotary kiln via a ram. Liquid wastes are generally injected by way of a lance in the front wall or in the post-combustion chamber.

In the rotary kiln the operating temperatures can be kept below (600 – 1050 °C) or above (> 1200 °C) the melting point of the slag, producing residues of different quality and properties.

¹ sewage sludge is only co-incinerated in grate firings

The degree of bottom ash burn out mainly depends on temperature, speed of rotation, length and the inclination of the rotary kiln. Both kiln and afterburner chamber are supplied with combustion air by way of the burners and via the end wall. Air seeps in via the rotary kiln sealings. The afterburner chamber is supplied with secondary air. If required, tertiary air is injected to cool down the flue gases before they enter the boiler in order to prevent clogging by fly ash.

In the rotary kiln primary air is injected via the front wall. Hence, the air and the flue gas moves alongside the waste bed. Since with grate firing primary air is supplied through the waste bed, fluctuations in the degasification process, in the calorific value and the moisture of the waste, can be compensated by controlling the air supply in the different combustion zones. This is not possible in rotary kilns. Thus, in order to keep the "fuel:heat output"-ratio at a constant level, a special feeding plan is required, particularly for waste fuels with high calorific value.

1.3.3 Fluidised bed incinerators

Fluidised bed incinerators are used for the combustion of easily proportioned wastes in industrial plants and the combustion of sewage sludge. In recent years the application of fluidised solid techniques has been extended to household wastes, following examples from Japan and Scandinavia.

Depending on their particular application, fluidised bed reactors are subdivided into bubbling, internally and externally circulating incinerators.

In bubbling fluidised bed incinerators the fluidised bed is kept in a bubbling suspension through injection of combustion air. The fuel is injected either from above the bed or directly into the bed. Depending on the pressure difference in the primary air ventilator, bed material is either fed or discharged. Stationary incinerators are mainly used for combusting municipal wastes, as well as for sewage sludge, barks and certain wastes from industrial plants.

In internally circulating fluidised bed incinerators the bed material is exposed to a constant circulation, mainly by the shape of the incinerator and the air supply pattern of the fluidised bed. In some cases also cooled and internally placed rebounding separators are used. The burnout of the gases only occurs above the circulating fluidised bed or downstream of the rebounding separators.

In externally circulating fluidized bed incinerators the combustible bed material is transported through the combustion chamber with the flue gases. Most of the solids are precipitated in downstream cyclones or rebounding separators and are then re-introduced into the combustion chamber.

The output of each fluidised bed system is directly linked to the amount of fuel charged. Whereas with grate firing and rotary kilns gasification and degasification processes can be controlled by air supply, in fluidised bed incinerators these processes take place spontaneously.

Combustion air is supplied through a distributor plate at the base of the combustor or blown in as secondary air overhead the circulating bed. Secondary air can also be supplied in several phases. Due to high-speed injection of secondary air and the special shape of the afterburner zone, the flue gases are thoroughly mixed with secondary air.

The emissions resulting from the combustion of waste materials in fluidised bed incinerators are discharged together with the flue gas, by way of the solid waste stream or the waste water. These emissions depend on the contamination of the fuel, the way it is fed, the shape of the combustion chamber, the reaction process and the firing in the reactor as well as in the applied flue gas cleaning system.

1.3.4 Pyrolysis with afterburner chamber

Pyrolysis is a thermal process (300 – 600 °C) for cracking organic substances into gas, tars and char. The residues thus consist of incombustible matter and carbon (pyrolytic coke). Pyrolysis is mostly used in smaller plants to treat high calorific commercial and medical wastes. These facilities are mostly operated discontinuously². In the pyrolytic step, temperature is regulated by the air supply. If pyrolysis is supplemented by gasification or incineration, coke is combusted leading to a burn out comparable to that of grate firing. This can be achieved through raising the temperature in the combustion chamber by introducing additional fuel. The gases generated in the process are high in energy and burned in an afterburner chamber.

Many processes of this type have been developed in the seventies as well as in recent years, e.g. Thermoselect, Schwel-brenn-Process, ÖkoGas etc. Certain steps of the incineration process (pyrolysis, degasification) are operated either isolated or in combination. It has been argued that one of the major advantages of such processes could be the production of more homogenous residues with better material properties. The lack of oxygen in the gasification gases reduces the de-novo-synthesis of dioxins, which poses a massive problem in incineration processes. Furthermore the separation of Cu at 1100 °C is possible in liquid elementary form, as is the separation of Pb either in elementary or sulphide form (Born, 1998). However these techniques are not yet state-of-the-art.

² Some systems can be assimilated to a two-stage combustion, featuring a pyrolytic and a combustion step

1.4 Emission Reduction Measures in Waste Incinerators

Compared to the flue gas cleaning techniques applied in combustors fired with conventional fossil fuel, the requirements for equivalent systems in a waste incinerator are toughened by three factors:

- a larger number of pollutants that have to be controlled and separated
- high concentrations of individual pollutants
- low threshold values specified by emission codes

Emissions into the atmosphere, waste water and solid residues, as well as emissions caused by required chemicals, and the input and output of energy have to be taken into account. It is important to note that the residues generated in the flue gas cleaning system have to be considered together with those of waste incineration in order to obtain a complete balance.

Depending on the selected technique and the input material, reusable materials can be recovered. Emission balances based on mass and energy balances are an adequate means for the comparison of technical alternatives and also for environmental impact assessment.

The major mass flow through an incinerator is the flue gas stream. Therefore emissions to air have to be considered with priority. As a first step the utilisation of already polluted air in the combustion chamber (e.g. from the waste collection pit), should be preferred over pure atmospheric air.

Flue gas cleaning systems usually consist of a combination of the following devices:

Boiler: Between 250 – 450 °C PCDD and PCDFs can be synthesised de-novo from components of the flue gas catalysed by ash particles. Therefore the hold-up time in this area should be kept as short as possible and dust accumulation on the walls should be avoided. At wall temperatures of about 400 °C corrosion through chlorides could occur.

Selective non-catalytic reduction SNCR: SNCR is based on the reaction of NO_x with NH₃ forming N₂ and H₂O at temperatures above 800 °C in the absence of a catalyst. NH₃ has to be added over-stoichiometrically to react with NO forming N₂ and H₂O. SNCR are most suitable for furnaces with appropriate temperatures in the combustion chamber (800 – 1000 °C). Negative effects are the emission of ammonia or its salts into air and water and irritating smells. These can be taken care of by scrubbers, thermal treatment of residues, strippers in waste water etc.

Selective Catalytic Reduction SCR: The use of catalysts for flue gas cleaning in waste incinerators is basically restricted to the reduction of NO_x and PCDD/F. The reaction temperatures range from 160 – > 300° C. In the SCR process ammonia is used to reduce NO and NO₂. The organic compounds are transformed to CO₂, H₂O and HCl. Catalysts have an expected life-time of five years.

De-dusting devices: De-dusting can be carried out using cyclones as a first step, followed by electrostatic filters or fabric filters, or just by using the latter. It is an advantage of the fabric filter over a cyclone or an electrostatic filter that the filter cake acts as an additional filter. They are used primarily after dry- and quasi-dry flue gas cleaning systems. De-dusting devices should not be operated at temperatures promoting the de-novo-synthesis of PCDD and PCDF (250 – 450 °C). The occurring dust would even enhance the reaction.

Dry flue gas cleaning systems: In these systems adsorbent is injected into either a fluidised bed or a flue injection reactor. They are operated with flue gases containing only low concentrations of pollutants. Adsorbent has to be added over-stoichiometrically. The generated residues and follow-up products are accumulated together with the excess of adsorbent. Possible adsorbents to remove HCl, HF and SO₂ are lime or sodium bicarbonate. Addition of activated carbon makes possible to remove also compounds of mercury and PCDD/PCDF (see below).

Quasi-dry flue gas cleaning systems: In these systems the hydrated lime is suspended before injection as a slurry. As in the dry FGC systems adsorbent has to be added over-stoichiometrically. This method can be used for medium concentrations of pollutant.

Wet flue gas cleaning systems: Depending on the pollutant concentration, these systems can be operated in one or two steps. The two-step approach has become very common in recent years. The first scrubbing step is operated at a pH < 1 to remove HCl, HF, SO₃ and soluble Hg-compounds. The second step is operated at neutral pH to remove SO₂ and the remaining HCl and HF. Hg occurs in flue gases in the form of HgCl, HgCl₂, HgO and metallic Hg. The most important parameter governing the proportion of each of the compounds is the temperature in the combustion chamber. At more than 850 °C the chlorides are prevailing. At lower temperatures the proportion of metallic Hg increases. Metallic Hg is not removable by wet scrubbers. Hence the temperature should be above 850 °C. It has to be taken care that the conditions in the scrubbing solution do not promote a reduction of dissolved Hg-compounds to metallic Hg. Reduction can be avoided operating at low pH or through addition of additives reacting with the Hg. In the second step, lime and NaOH are most commonly used as neutralisation media.

The definitive choice of the neutralisation medium is depending on the further treatment of the precipitated substances or reaction products. If it is impossible to discharge the chloride load into a body of water, lime may be chosen. Before final discharge of the waste waters, the fluorides precipitated in the first step can be precipitated as calcium fluoride and the SO₂ load of the second step as gypsum. The HMs can be precipitated as hydroxides. If the chlorides can not be desposited, dry scrubbing will be performed. The solution exiting the scrubber and the downstream waste water treatment unit will be led back to a spray-cooler, which is placed upstream the wet scrubber. In the downstream dust collector, the dried salts are precipitated. This salt load is highly hygroscopic, soluble in water and rich in contaminants, which necessitates underground disposal.

Fixed bed reactors: Fixed bed reactors with activated carbon are used downstream for the precipitation of PCDD/F and Hg. The remaining SO₂ and HCl are trapped at the same time. The activated carbon has to be cooled constantly since reactions between the carbon and the pollutants take place under exothermal conditions. In case of inadequate cooling self-ignition of activated carbon may occur. In most applications fixed bed reactors are used, however in some cases also slow-moving bed reactors, flue injection or fluidised bed reactors are applied.

Generally the choice of a combination of the above mentioned flue gas cleaning devices will depend on the attempted off-gas concentration and the targeted form of the residues (e.g. regarding recovery or disposal).

1.5 Residues

Waste incineration generates gaseous, liquid and solid reaction products. Solid residues are produced in several stages of the combustion process and many different definitions can be found in literature. The following terms are used frequently:

- Bottom ash (also referred to as slag) is a solid residue that does not escape with the flue gases. It accumulates at the end of the grate (grate ash) or drops down between the grates (grate riddlings).
- Boiler ash occurs at the heating surface of the boiler, being collected in the funnels below.
- Filter dust are the particulates separated from the flue gas by electrostatic or fabric filters.
- The term "Fly ash" summarizes boiler ash and filter dust. Boiler ash only presents 10-20% of the total fly ash depending on the applied technology. The terms fly ash and filter ash are often used interchangeably.
- The term "reaction product" is used in this context for the solid material produced in dry or quasi-dry flue gas cleaning. Also residues from wet scrubbing are included in this group. It can contain fly ash in case the latter is not separated in a de-dusting step prior to flue gas cleaning. In the following text, the terms "reaction products" and "air pollution control residues", APC, are used interchangeably.

The amount and the composition of the incineration residues is very much dependent on the composition of the input material (as discussed in Chapter 1.2), the firing technique (as discussed in Chapter 1.3) and the selected flue gas cleaning method (as discussed in Chapter 1.4).

Table 3: Common ranges of residues from 1 Mg of municipal waste (Status Report, 1996; Dobris Report, 1995)

Residue type	Residues from 1 Mg of waste	
Bottom ash	250-350 kg/t	
Boiler ash	2-12 kg/t	
Filter dust	20-40 kg/t	
Filter dust + reaction product	40-80 kg/t	
APC residues	Excluding dust	Including dust
▪ Wet process	8-15 kg/t	30-50 kg/t
▪ Quasi-dry process	15-35 kg/t	40-65 kg/t
▪ Dry process	25-45 kg/t	50-80 kg/t

Table 4 presents approximate ranges of the elementary composition of the individual residues. The residues do not occur in elementary form, but in form of chemical compounds, mostly as oxides, but also as chlorides, sulphates etc. Since it is difficult to determine the actual form in which certain elements are bound, this form of presentation has been chosen. The given ranges are sometimes quite large due to the varying composition of the input material.

Table 4: Elementary composition of residues from waste incineration

Residue/ Element (g/kg)	Elements in the Earth Crust (g/kg) (Krauskopf, 1979)	Bottom ash (Reimann, 1994)	Filter dust (Reimann, 1992 / ATV, 1998)	Filter dust + reaction product (Reimann, 1992)
Spec. Accumulation		250-350 kg/t	20-40 kg/t	40-80 kg/t
Si	130 g/kg	140-320 g/kg	105-150 g/kg	30-50 g/kg
Al	82 g/kg	5-95 g/kg	60-120 g/kg	17-48 g/kg
Ca	41 g/kg	30-140 g/kg	30-90 g/kg	230-390 g/kg
Na	24 g/kg	5-35 g/kg	20-80 g/kg	4-20 g/kg
Mg	23 g/kg	4-16 g/kg	28-40 g/kg	6-11 g/kg
K	21 g/kg	5-20 g/kg	12-74 g/kg	12-32 g/kg
Fe	56 g/kg	20-110 g/kg	28-40 g/kg	4-12 g/kg
P	1.1 g/kg	3-34 g/kg	1-12 g/kg	0.5-3 g/kg
S	0.26 g/kg	2-4 g/kg	20-40 g/kg	14-37 g/kg
Cl	0.13 g/kg	0.3-6.3 g/kg	40-78 g/kg	100-200 g/kg
C	0.2 g/kg	5-50 g/kg	14-36 g/kg	9-27 g/kg
CO ₃	–	7-15 g/kg	1-5 g/kg	3-17 g/kg
Cu	0.06 g/kg	0.2-7 g/kg	0.7-2 g/kg 0.1 5-5 g/kg	0.2-0.8 g/kg
Cr	0.1 g/kg	0.1-9.6 g/kg	0.5-1.7 g/kg 0.05-2 g/kg	0.03-0.2 g/kg
Zn	0.07 g/kg	0.5-21 g/kg	13-39 g/kg 5-40 g/kg	6-17 g/kg
Pb	0.0002 g/kg	0.6-5.2 g/kg	6-12 g/kg 1-14 g/kg	1-7 g/kg
Ni	0.08 g/kg	0.04-0.76 g/kg	0.2-0.3 g/kg 0.1-0.4 g/kg	0.02-0.2 g/kg
Cd	0.0002 g/kg	0.0001-0.082 g/kg	0.2-0.6 g/kg 0.05-1 g/kg	0.09-0.3 g/kg
Hg	0.00008 g/kg	0.0001-0.02 g/kg	0.002-0.025 g/kg 0.001-0.03 g/kg	0.002-0.03 g/kg
Dioxin I-TEQ		7.2-25 ng/kg	0.5-30 ng TE/g	
PAH		13-19.000 mg/kg (IAWG, 1997)		

The solid residues are characterised by an environmentally harmless matrix consisting of various silicates and oxides of Si, Al, Ca, Mg, Na and K. These are contaminated with organic³ and inorganic⁴ substances, some of them posing a threat to the environment. The degree of heavy metal contamination is especially obvious if the HM-concentrations in the residues are compared to those in the earth crust (see 2nd column). Especially the concentrations in filter dust can be about 100 – 1000 times above the concentrations in the earth crust (Hundsrückge, 1990) in case of volatile elements, e.g. Hg and Cd. Elements that are not easily volatilised, such as Cr and Cu remain mostly in the bottom ash (Knorr et al., 1999).

Concerning organic compounds in the residues, literature data are in most cases only available for TOC and for selected contaminants.

PCDD/PCDF are mostly found in fly ash and the flue gas. Bohlmann, 1995, measured the following concentrations of PCDD/PCDF in different residues:

Table 5: PCDD/F in different residues [Bohlmann, 1995]

Sampling location	PCDD/F in I-TEQ
Bottom ash	0.6-10 ng/kg
Bottom ash + electrofilter dust	380-830 ng/kg
Boiler ash	100-800 ng/kg
Electrofilter dust	1000-28000 ng/kg
Filter cake	2000-31000 ng/kg

They can originate either from the waste input or can be generated de-novo in the boiler between 200 – 500 °C. The generation of PCDD/PCDF can therefore be controlled via the temperature of the flue gas.

PCB and PAH are mostly found in bottom ash and grate riddlings. This value is very much dependent on the firing technology and is an indicator for the degree of bottom ash burn-out. This becomes obvious in the next table, presenting ranges of PAH concentrations in the residues of different Canadian waste incinerators (Chandler, 1997):

Table 6: PAH in different residues

PAH in Bottom ash	PAH in Boiler ash	PAH in Filter dust
125-19000 ng/g	12-6430 ng/g	30-1050 ng/g

Bottom ash is the prevailing residue considering the generated mass. Leaving the elementary composition aside, bottom ash consists of

- 3 – 5 % uncombusted material
- 8 – 10 % ferrous and non-ferrous metals (tinplate, copper, brass, aluminium, alloys, etc.)
- 4 – 5 % coarse material (> 32 mm; concrete, bricks, stones, slag chunks)
- 80-85 % fine grained material (< 32 mm, as above, + glass, ceramics, porcelain, domestic heating ash)

The fraction < 8 cm contains the highest amount of contaminants.

3 halogenated hydrocarbons such as dioxins and furans

4 heavy metals, such as Cu, Cr, Ni, Zn, Pb, Cd and Hg mostly in form of chlorides and sulphates

The carbon contents of incinerator residues from modern incineration facilities after treatment should not exceed 1 – 3 %w. This could influence the mobility of heavy metals and trigger degrading processes. Most of the carbon is found in the fine grained fraction.

Grate riddlings usually contain a higher amount of uncombusted material than the rest of the grate ash and also substantial quantities of metallic Al, Pb and Cu (IAWG, 1997). After removal of the metals, the grate riddlings could be transferred back to the combustion chamber to reduce the total carbon content (Knorr et al., 1999). Due to the elevated HM-level of grate riddlings, the International Ash Working Group IAWG emphasised this as an area of concern if bottom ash is destined for utilisation application.

The chemical composition of boiler ash and air pollution control residues can vary depending on the input material (waste), the concept of the plant and the operating conditions (Chandler et al. 1997). Also the chemical composition of fly ash and air pollution control residues are dependent on the above mentioned factors. They are both highly hygroscopic and often occur in form of agglomerates (Birnbaum et al., 1987), a facet that is used in the Bamberg Model (see below)⁵.

⁵ In many countries regulations for fly ash and air pollution control residues can differ widely. In Germany for instance fly ash may be disposed of above ground, APC has to be disposed of underground (IAWG, 1997).

1.6 Treatment of Residues

Incineration residues shall only be recovered, if it is environmentally sensible and technologically and economically feasible. Furthermore it has to be assured that the costs of recovery are not unreasonable and that there are markets for the individual products. If these criteria are not met, residues should be treated in a way that disposal in a stable and inert form is possible.

In order to reduce potential hazards from solid residues, the following treatment methods can be applied:

- Solidification
- Separation
- Scrubbing
- Low-temperature and incineration processes
- Melting, sintering, vitrification and plasma techniques

1.6.1 Solidification

Solidification processes are also referred to as conditioning, stabilising or immobilising processes. They aim at reducing the mobility or the mobilisation potential of certain pollutants. Solidified material should meet the following criteria:

- Low permeability for water
- No chemical reaction with water
- Mechanical long-term stability
- Chemical and biochemical long-term stability of immobilised substances as well as additives
- No potential exceedance of the drinking water thresholds in the long term, due to erosion, corrosion or changes in the disposal conditions
- No emission of any kind of metabolites of environmental concern
- Compatibility with follow-up processes

It is possible that an immobilisation procedure only immobilises certain pollutants. Therefore a thorough knowledge of the immobilisation mechanisms is of utmost importance. The basic mechanisms are⁶:

- Encapsulation
- Physical integration into homogenous solidifying phases such as polymeres, glass or other silicates
- Integration through chemical reaction with the waste, e.g. lime

A decision which mechanism to chose has to be made individually. In general, since most of the binding systems are based on inorganic matter, inorganic pollutants such as HMs can be immobilised easier than organic compounds.

Harmful substances in filter dust and air pollution control residues can be immobilised adding binders. In this case immobilisation is necessary to ameliorate the leaching behaviour before disposal, since a reuse of the solidified material is not possible due to the high concentrations of soluble HMs and salts in these residues. Common processes, using cement as a binder, are the Slag-Residue-Additive-Process and the Cement-Additive-Process. In the Slag-Additive Process the input materials are bottom ash, fly ash, APC and

⁶ Obviously melting is also a method of immobilisation, but it is discussed separately below.

cement, in the Cement-Additive-Process fly ash, filter dust, filter cake and salts from APC. Apart from cement, other inorganic and also organic binders have been suggested in literature. The products can be formed to any shape, the surface however has to be sealed.

The following Table presents typical binder reagents (IAWG, 1997):

Table 7: Binder reagents

Wastes	Commercial	Bitumen	Polymeric
Cement kiln dust	Portland cements	Hot emulsion	Epoxy
Blast furnace slag	Lime	Cold emulsion	Polyesters
Lime kiln dust	Limestone		Polyolefins
Coal fly ash	Quicklime		Urea Formaldehyde

Inorganic binders are normally chosen because of their lower costs. Polymers are the most expensive binders. They do not react with the waste, but rather encapsulate the materials. Also combinations of organic and inorganic binders have been proposed (IAWG, 1997)

In the Bamberg Model, dust from electrostatic precipitators is mixed with sorption sludge in the proportion 1:2. The pasteous product is setting in relatively short time without further addition of binders, forming a dust-free, impermeable material that can be used as a covering layer for landfills. The Bamberg Model is used in some Swedish incineration facilities. The main advantage of the Bamberg-Model is, that it is not necessary to add high-quality products such as cement and calcium hydroxide, avoiding high costs for conditioning and transport. However the leaching properties of residues solidified with additives were found to be better than those of the self-solidification process.

1.6.2 Separation

The physical separation of grate ash, but especially grate riddlings always includes a metal separation step. Eddy-current separators allow non-ferrous metals to be largely separated. The remaining material is sometimes transferred back to the combustion chamber for better burn-out.

1.6.3 Scrubbing

1.6.3.1 Bottom Ash

Bottom ash outweighs the other residues by far according to the produced mass (250 – 350 kg/Mg of waste). It is state-of-the-art to recover iron scrap from the bottom ash using magnetic separators (about 40 kg of the given 250 – 350 kg bottom ash / Mg waste). Mixing with grate riddlings should be avoided if possible because of its content of metallic aluminium.

The MR (Multi Recycling) -Process is an integrated bottom ash and fly ash treatment process. In the wet scrubber, soluble compounds (chlorides, sulphates etc.) are extracted either with the scrubbing solution of the 2nd step of the flue gas cleaning system or with fresh water in case of a separate recovery of gypsum. Gypsum is precipitated after addition of CaO. A part of the scrubbing solution has to be led back to the 1st step of the flue gas cleaning system to avoid accumulation of chlorides in the system. The treatment of the fly ash shall be discussed in the next section.

In the Bamberg Slag Washing Concept, the bottom ash is quenched in a wet scrubber and washed at 60 °C for about 15 min to dissolve soluble salts (e.g. chlorides) and - depending on the pH - a fraction of the heavy metals. This washing process leads to a moisture content of 20 – 30 %, that is reduced to about 15 – 25 % in a subsequent de-watering step.

After that the bottom ash is classified and subject to an ageing process of two to three months, leading to further dewatering and increasing stability of the volume through recrystallisation of metal hydroxides.

The bottom ash can be washed either directly after incineration or after mechanical processing and the ageing process (L.&C. Steinmüller-Process)

The so-called Bielefeld-Concept aims at keeping very ambitious thresholds for drinking water through a four-step process: mechanical processing, ageing, leaching and conditioning. The conventional processing consists of the recovery of ferrous scrap, the separation of incombustible matter, classification etc. The ageing process is a controlled long-term storage under humid conditions to finish all processes requiring just little water (e.g. formation of carbonates, oxidation forming sulphate, electrochemical precipitation of metals nobler than Fe, formation of hardly soluble heavy metal compounds). The leaching step removes the easily soluble neutral salts (Na, K, Cl, SO₄). Conditioning is necessary for long-term buffering against changes in pH. This is carried out adding fine grained building rubble or concrete (10–20 w%).

Leachate and washing liquid have to be collected and treated together with the liquid residues from flue gas cleaning.

The InRec^{plus}-Process is based on dry bottom ash discharge with subsequent sorting. Compared to conventional wet bottom ash processing, more metals in a better quality are recovered, as corrosion and cementation is prevented. In addition, the main mineral fraction is not only low in metals, but can also be further cleaned from organic carbon, salts and heavy metals with simple mechanical means. With two complementary thermal processes, InRec^{plus} covers a wide range of ash vitrification demands, and finally features a patented method to turn the glassy melt into foamy slag that could be used in civil construction (Selinger et al., 2000).

1.6.3.2 Filter dust and reaction products

Chlorides and heavy metals (depending on the pH of the solution) can be dissolved in wet scrubbing steps similar to those used for bottom ash.

HMs can only be dissolved at low pH, a fact that is used in the 3R-Process. Fly ash is extracted with acidic water from the HCl-scrubber⁷ (pH 0.5-1.5), the first step in the wet flue gas scrubbing system, and de-watered together with the gypsum and sludge from the multi-step waste water treatment. The mixture is then solidified with 20 %w of binding material and transferred back into the combustion chamber to destroy organic substances.

The pH has to be controlled continuously since the alkaline effect of the filter dusts leads to steady increase in pH in the scrubbing solution. Dissolved heavy metals have to be precipitated from the scrubbing solution in form of insoluble hydroxides or sulphides. These neutralisation sludge can be solidified together with the washed residues. The washing solution does still contain chlorides and has to be treated separately.

Washing processes for fly ash and air pollution control residues can be carried out under acidic or alkaline conditions.

⁷ Mercury compounds are removed using ion-exchange chromatography.

In the MR-Process fly ash treatment is carried out in two steps: a leaching step with water and a thermal treatment step. In the leaching step fly ash is first dispersed in water and stirred for 10 min leading to a pH of 9 – 12. This alkaline pH is controlled to avoid HM-dissolution. As opposed to acidic treatment, this reduces the necessary amount of expensive absorption material (NaOH), since the alkaline compounds of the fly ash enhance the SO₂-precipitation. It also reduces the disposal costs since sulphates do not appear as gypsum in the water treatment system.

The second leaching step is carried out under acidic conditions to extract HMs.

The thermal treatment step is necessary to destroy dioxins. Mercury evaporates from its adsorption sites on the fly ash into the flue gas and is trapped to 95 % in an activated carbon filter.

As an alternative to the solidification, fly ash can be returned to the combustion chamber after a wet scrubbing step to destroy organic substances.

In the Sulzer Chemtech Washing Process, fly ash and APC are suspended in water. After addition of waste water treatment sludge, the pH is set to > 9 using NaOH, which leads to precipitation of HMs in form of hydroxides. The solid residues and the filtercake are dewatered and solidified. The filtrate and washing water have to be treated.

Wheelabrator Technologies Inc. promotes a patented and commercially proven process for chemically treating municipal solid waste combustion fly ash to reduce the leaching of certain heavy metals. The addition of phosphate to ash reduces the leaching of lead and other metals by converting soluble compounds, such as Pb(OH)₂, into more stable and insoluble mineral phases (Lyons, 2000)

Another process, which enables the reuse of air pollution control residues is the NEUTREC Process. The NEUTREC Process is based on a dry flue gas cleaning system, which uses the injection of sodium bicarbonate. The process can be divided into exhaust gas cleaning and treatment of the residues from the exhaust gas cleaning.

The first step of the exhaust gas cleaning is an electrostatic precipitator, which separates most of the fly ash from the exhaust gas. After the ESP sodium bicarbonate and activated carbon are injected into the flue gas to separate HCl, SO₂, HF, PCDD/F and heavy metals from the flue gas. The dry residues from the exhaust gas cleaning, mainly consisting of sodium containing reaction products (NaCl, Na₂SO₄, Na₂CO₃), activated carbon and fly ash, which was not separated in the ESP and heavy metals, are subsequently separated from the flue gas with fabric filters.

The second step is the treatment of the air pollution control residues, which have been separated with the fabric filters. An industrial pilot plant, which treats 2 800 t of these residues per year is in operation since 1998 in Italy. In a first step the residues are dissolved in water. To separate the brine from the insoluble components and the heavy metals the solution is lead over a filter press. The filter cake separated in the filter press has to be landfilled. The amount of filter cake is approximately 2 – 4 kg/t incinerated waste.

After the filter press the brine is purified with a sand filter and with activated carbon filtration, especially to remove organic substances. To remove the rest of heavy metals from the brine ion exchangers are used. The washing water and the regeneration solution of the ion exchangers are completely recirculation and used as water to dissolve the air pollution control residues. Therefore no waste water is produced during this process. Table 8 shows the typical composition of the air pollution control residues and of the produced, cleaned and saturated brine. All values are given on a dry base.

Table 8: Composition of air pollution control residues and produced brine [Bauer et al., 2000]

Component	Air pollution control residue	brine
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Component	Air pollution control residue	brine
NaCl	65 %w	70 %w
Na ₂ SO ₄	10 %w	10 %w
Na ₂ CO ₃	15 %w	15 %w
KCl	2 %w	2 %w
insoluble substances	4 – 8 %w	< 0.004 %w
Metals		
Al	1.8 mg/kg	4 mg/kg
Co	7 mg/kg	< 0.1 mg/kg
Cr	35 mg/kg	< 0.4 mg/kg
Cu	480 mg/kg	< 0.4 mg/kg
Hg	95 mg/kg	0.2 mg/kg
Pb	2.6 mg/kg	4 mg/kg
Zn	6.2 mg/kg	< 0.4 mg/kg

An other possibility of this process is that no electrostatic precipitator is used for the separation of the fly ash. The fly ash is separated and treated together with the air pollution control residues. The amount of landfilled filter cake from the filter press is higher, when this process is used.

A new process, which is currently under development tries to reuse all residues from the exhaust gas cleaning. The fly ash is first wash and then lead to a filter press. The residues from the filter press are chemically and thermally treatment. The washing solution from the filter press is used in the NEUTREC process as water to dissolve the air pollution control residues. First results of this pilot plant can be expected in 2003.

1.6.4 Low-temperature- and incineration processes for filter dusts, reaction products and laden activated coke

The **low-temperature processes** are based on catalytic decontamination. In the presence of catalysts, PCDD and PCDF, as well as other chlorinated aromatic hydrocarbons are destroyed effectively at temperatures between 150 and 500 °C. Filter dusts, reaction products and laden activated coke from waste incinerators show this effect at 300 – 400 °C. The destruction mechanisms are basically dechlorination and dehydrogenation. At these temperatures, the access of air oxygen has to be blocked in order to avoid the rate of de-novo-synthesis to be higher than the destruction rate. However treated filter dusts can still not be utilised in any way, due to their high heavy metal and salt content, that is not changed by the treatment.

The Hagenmaier-Process aims at a catalytic destruction of dioxins. The input material is fed into a drum and heated to 400 – 450 °C in a reducing atmosphere. The material is mixed by a rotor. Afterwards the material is transferred into another drum and cooled down to 80 °C, avoiding contact with ambient air.

Another method is used in the third step of the MR-Process (see above). A rotary kiln is used for heating. Cooling is carried out in a water-bath. In the Swiss Von Roll-Process flue gases from gas- or oil combustion are used to heat the input material, where it is kept for four hours at 400 °C before cooling.

The W. Wruss Concept for fly ash and APC aims at removing Hg and Hg-compounds as well as PCDD/F through oxidising thermal treatment at 600 – 700 °C. At 800 °C even As, Sb and Zn can partly be removed from the residues.

Incineration processes are usually used for thermal destruction of organic matter. The generated flue gases can - with or without energy recovery - be transferred back directly to the combustion chamber or to the flue gas cleaning system. The heavy metals trapped in activated coke filters are not destroyed by high temperatures, but evaporate once more into the flue gas. Hence they have to be led back to the flue gas cleaning system.

Laden activated coke filters can be incinerated in grate firing or rotary kilns together with municipal or hazardous waste directly or after low-temperature treatment. Alternatively they can be incinerated in separate combustion chambers, such as cyclone, cycloid or rotating combustion chambers. Either combustion air or an air-carbon-mixture produce a rotating flow to keep up the hold-up time and the burn-out.

The melting cyclone, as used in coal fired power plants, consists of an inclined combustion chamber, where laden activated coke is blown in tangentially. The generated heat is usually recovered. It is also possible to treat boiler and filter dust together with the activated coke. Depending on the ratio coke : dust, additional fuel might be necessary.

The cycloid furnace consists of a vertical cyclone that is fed with carbon from one side. Combustion air is blown in tangentially. Due to centrifugal forces the burning carbon particles stay in rotation until they are burned to the threshold diameter and blown out with the flue gas.

In dust-firing the combustion material has to be ground before incineration for good burn-out. The carbon- air mixture is blown directly into the vertical combustion chamber. If there is no sink for mercury in the flue gas treating system, it has to be de-sorbed before incineration.

In the CT Fluapur-Process the evaporated HMs are not trapped in an activated coke filter, but are collected as a condensate in HCl-enriched atmosphere and may be recycled in metallurgical plants. The remaining sand like product can be re-used as concrete additive. There is a possibility to produce Alinite cement from fly ash and air pollution control residues in a rotary kiln. Since the process is operated at 1 000 – 1 100 °C, laden activated coke can be used as supplementary fuel at the same time as using the process as a sink for PCDD and PCDF. Alinite cement is subsequently ground and can replace Portland cement in underground dumps or in landfills.

1.6.5 Melting, sintering, vitrification and plasma processes for bottom ash and dust

Melting processes aim at destroying POPs and removing volatile HMs at the same time as generating re-usable products with enhanced leaching stability.

Depending on the process and the input material, the products can be :

- Ferrous and non-ferrous metals
- Stones, glass, ceramics
- Melting granules
- Zn-Pb-concentrate
- Hg-concentrate
- Salts from flue gas treatment

Fe- and non-ferrous metals can be recovered in metallurgic processes.

The shares of silicates and aluminium oxides, originating from glass, ceramics, cement and concrete in waste, are forming aluminosilicate-melts at temperatures above 1250 °C. These solidify to either amorphous or crystalline silicate products. The organic substances are completely destroyed at these temperatures. The behaviour of the heavy metals is very much dependent on the process conditions:

- The products of the oxidising processes still contain heavy metals of environmental concern but they are incorporated physically into the amorphous or crystalline matrix. The products show a relatively good leaching behaviour, but there is no long-term guarantee for immobilisation.
- Under reducing conditions, a combination of chemical reaction and physical separation allows an even better removal of pollutants. Carbon for instance reduces heavy metal oxides to their elementary forms. The volatile ones (Zn, Cd, Pb) evaporate, the others (Fe, Ni, Cr, Cu) are separated from the other melted residues according to their different densities. Under reducing conditions, a separation and recovery of the residual metals is possible.

The following Table presents the variety of different processes that are available. Not all these processes are at present in use on an industrial scale. Therefore this Table should only be seen as an idea which processes exist.

Table 9: Variety of the different processes available

Type	Name of process	Technology	Input material
integrated	Conversion/GSP	Flue injection gasification	Sewage sludge/waste
	HTV	Gasification reactor	Waste
	Contop	Melting cyclone	Sewage sludge/waste
	Cyclone-gasification	Cyclone	Sewage sludge
	Aicher	Ash furnace	Sewage sludge
	KMSF	Furnace	Sewage sludge/waste
	Plasmox	Plasma combustion	Plasma electrodes
	Schwebbrenn	Combustion chamber	Waste
	Thermoselect	High temperature reactor	Waste
	DBA	Melting chamber	Waste
	PyroMelt	Furnace	Waste
	ÖkoGas	Gasspalter	Waste
	Duotherm	Rotary kiln	Waste
	Volund	Rotary kiln	Waste
VS	Rotary kiln	Waste	
ARS	Refractory-covered tube	Gas, oil	
Follow-up	Conversion/GSP	Flue injection gasification	Waste, gas, oil
	Contop	Melting cyclone	Coal, gas
	KMSF	furnace	Gas, oil, waste
	Revitron	Ash furnace	Gas
	FosMelt	Ash furnace	Gas
	SHT	Ash furnace	Gas

Type	Name of process	Technology	Input material
	Solur	Ash furnace	Mo-electrodes
	MANGHH/SORG	Ash furnace	Mo-electrodes
	Deglor	Electric furnace	Electrodes
	Plasma	Plasma burner	Plasma electrodes
	HES	Electric furnace	Electrodes
	HSR	Converter	Gas, oil
	OxiMelt	Kupol-furnace	Gas
	RedMelt	Arc furnace	Graphite electrodes
	EloMelt	Arc furnace	Graphite electrodes
	InRec	Arc furnace	Graphite electrodes

Melting processes can be integrated into the combustion process or can be operated as follow-up processes.

Processes with integrated melting can be carried out in either one or more steps. In a one step process the waste is incinerated and the ash is taken out in melted form (Contop, KMSF) leading to much better material properties of the residues. In the HTV- and Cyclone-gasification-Process, gasification and melting is combined in the same process. The generated gas can be burned in a further aggregate.

Other processes have got an additional thermal step before the melting step. In some cases (Schwelbrenn, PyroMelt, Konversion, DBA) it is a pyrolysis drum, in the Thermoselect-Process a vertical channel and in ÖkoGas a fluidised-bed reactor. In some of the processes the gas-particulate-mixture is not combusted completely, but is used to fuel gas-motors. In some cases methanol is synthesised instead of incineration. In the Duotherm and the VS-Process, gasification is carried out in a conventional grate firing installation, incineration and melting in a rotary kiln. Both the combustion and the melting facility can be operated separately. The generated flue gases contain HMs and salts, that are condensed in a filter. The produced concentrate can be processed metallurgically. The remaining flue gas is usually led back to the flue gas cleaning system of the incineration facility.

If the melting step is not integrated into the incineration step, Ash- or Arc Furnaces similar to those in metallurgic processes are used for heating. Most of the these processes are operated under oxidising conditions.

RedMelt and EloMelt are processes operated under reducing conditions in an Arc furnace with carbon electrodes.

The HSR-Process starts the melting process under oxidising conditions, followed by a second step under reducing conditions.

In the Solur-Process fly ash and reaction products are melted simultaneously, which is difficult because of the high concentration of chlorides and sulphates in the reaction products, that can not be incorporated into the glass phase. The salts form a separate phase and have to be disposed of in underground dumps.

The InRec^{plus}-Process is based on dry bottom ash discharge with subsequent sorting. Compared to conventional wet bottom ash processing, more metals in a better quality are recovered, as corrosion and cementation is prevented. In addition, the main mineral fraction is not only low in metals, but can also be further cleaned from organic carbon, salts and heavy metals with simple mechanical means. With two complementary thermal processes,

InRec^{plus} covers a wide range of ash vitrification demands, and finally features a patented method to turn the glassy melt into foamy slag that could be used in civil construction (Selinger et al., 2000).

Fly ash can also be melted by plasma electrodes, reducing its volume by 70 %. Furuta et. al. (2000) carried out solubility tests of the molten slag at pH values between 1 – 9. In order to quantify watertightness, static capacitance etc. were measured after 1 year. The molten slag showed a good endurance after eluting for a period of 1 year.

Which criteria should therefore be applied to choose a melting process? For existing incineration facilities only follow-up melting steps are possible. However they have also got advantages for new plants due to their flexibility and stability. If follow-up melting is only a means to ameliorate the properties for disposal, it might not be an environmentally sensible solution. However in case of a recovery of materials that could substitute others saving energy and resources at the same time, it could be the preferred option. The decision has to be made for each case individually.

Sintering is an alternative to the above mentioned melting

leads to even better leaching stability than actual melting. Melted products normally contain less volatile organic matter, however the immobilisation of HMs is about as good in amorphous glasses as in crystalline matrices.

Boccaccini and Kern (2000) applied powder technology and sintering to transform a vitrified municipal incinerator fly ash into glass-ceramic products. The sintered material showed attractive mechanical properties, i.e. relatively high fracture strength and toughness and high thermal shock resistance. The authors argue these products had a large application potential, especially as construction and building material. However open questions concerning the chemical durability and toxicity of the products remain, and they must be fully answered before these glass-ceramics can be realistically considered for the envisaged application.

The following Table gives an overview of the treatment methods discussed above (Papp, 1996):

Table 10: Treatment methods for residues from waste incinerators

Technology	Treatment method	Treatable Residue	
Separation	Separation of Ferrous and non-ferrous metals	BA	
Solidification	Slag-Residue-Additive-Process	BA / FA / APC ⁸	
	Cement-Additive-Process	FA / APC	
	Bamberg Model	FA / APC	
Leaching / scrubbing	Bielefeld Concept	BA	
	Bamberg Slag Washing Process	BA	
	L. & C. Steinmüller Washing Process	BA	
	MR-Process	BA / FA	
	3R-Process	FA	
Low-temperature processes	Sulzer Chemtech Washing Process	FA / APC	
	Hagenmaiertrommel	FA	
	Wruss Concept	FA / APC	
	Von Roll Process	BA / FA	
Melting processes	MR-Process	BA / FA	
	oxidising	Babcock Technology	BA / FA
		FosMelt-Process	BA / FA
		KSMF Melting Process	BA / FA / Coke
		Glass-Melt-Process	FA / APC
		Electromelt-Process ABB	FA
		Melting Cyclone KHD	FA / Coke
		Schwebbrenn-Process	FA
		Noell-Gasification	FA / Waste
	reducing	RedMelt-Process	BA / FA
		Mannesmann Hollow-Electrode-Process	BA / FA
		HSR Process	BA

⁸ BA...Bottom Ash; FA...Fly Ash; APC...Air Pollution Control

Technology	Treatment method	Treatable Residue
	Plasma-Melting-Process Thermoselect Process	FA BA / FA
Disposal	Alinit Binder Hydraulic Binder Mine packing material	FA / APC FA / APC FA / APC

The choice of a treatment option is very much dependent on the quality of the residues and the intention of its future use. It is also important that a treatment option is chosen on the basis of the envisaged environmental goal and of reasonable costs for the aspired operation. An amelioration of residue quality can be achieved through high expenses in financial and energetic terms (Schaub, 1996). In the individual case, a decision has to be made whether or not the expenses are balanced by the outcome. In Great Britain, for example, this approach is even reflected in legislation, which requires that operators use the Best Available Technique Not Entailing Excessive Costs (BATNEEC).

1.7 Utilisation and Disposal of Residues

Incinerator residues are considered for a variety of applications in many countries. Interest in utilisation is principally motivated by the potential for saving landfill capacity (hence reducing disposal costs) and the substitution of natural aggregates. The relative importance of each of these factors varies considerably from country to country (IAWG, 1997).

In practice, there are numerous obstacles to utilising incinerator residues (IAWG, 1997):

- Existing regulations
- Lack of economic incentive
- Liability issues
- Residues separation practices
- Uncertainties concerning the functional properties of the residues
- Uncertainties concerning the evaluation of the extent and acceptability of the environmental impacts and health hazards.

In the USA for instance only about 5 % of the incinerator residues are recovered. In some European countries recovery of residues plays a more important role. In Germany about 50 % are recovered. Denmark recovers 72 % and The Netherlands are even aiming at more than 80 % recovery.

The following table presents the approaches of certain countries towards utilisation of residues (IAWG, 1997):

Table 11: Utilisation of incinerator residues

Country	Utilisation
Canada	Availability of landfill space -> little incentive to pursue utilisation Bottom ash sometimes utilised for road construction
Denmark	Most of the BA utilised for civil engineering purposes
Germany	50 % of the BA utilised, scrap recovery APC -> pilot scale evaluation for use as filling and sealing material in coal mining
The Netherlands	Government policy to achieve utilisation of more than 80 % of the total residues due to lack of landfill space in practice: 95 % of BA utilised already
Sweden	Currently very limited utilisation due to regulations for licensing the use of any residual products in a specified manner
United States	Shortage of existing landfill space -> many planned or ongoing demonstration projects

In the following section the possibilities and the sensibility of recovery are discussed for each of the residues individually.

1.7.1 Bottom ash

The main part of the generated residues is bottom ash (250 – 350 kg from 1 Mg of waste). It outweighs the other residues by mass and is therefore the most important fraction considering treatment, utilisation and recovery.

The most important parameters for the recovery of bottom ash are the TOC (total organic carbon), the content of salts (chlorides and sulphates⁹) and the HMs in the leaching test.

The recovery of metals from bottom ash is state-of-the-art. From 300 kg of bottom ash it is possible to recover about 40 kg of iron scrap. However the quality standards for input materials in iron- and steel plants are getting increasingly strict and are often not met by the recovered material. Aluminium, copper and other metals can be recovered by means of eddy-current separators.

After removal of the metals, the remaining bottom ash could be used for various applications, such as road aggregates, fill material, admixture in soil stabilisation, masonry bricks, cement replacement material, daily cover in landfills, wind and sound barriers or as dams in areas of suitable hydrology. In any case the bottom ash has to be stabilised in an ageing process before use. The surface has to be covered with a layer of very low permeability.

Theoretically the market for bottom ash in the building industry could be rather large. However the recovered material does in many cases not meet the quality standards for input materials in certain production processes. Secondly the heavy metal content of building material containing waste incinerator residues can be a problem for secondary materials management when the construction is later demolished. Furthermore, and this is an even greater problem, products recovered from waste incineration residues lack public acceptance and hence market value. An additional consideration that renders utilisation undesirable, is the absence of a clear definition of potential product liability.

The German "Länderarbeitsgemeinschaft Abfall" (LAGA) gives some values for the reuse of bottom ash from municipal waste incinerators. A part of these values is given in Table 12.

Table 12: Reuse of bottom ash from municipal waste combustion [LAGA, 1997]

values for the bottom ash	
TOC	1 w.%
EOX	3 mg/kg
values for the leachate of the bottom ash	
Pb	50 µg/l
Cd	5 µg/l
Cr	200 µg/l
Cu	300 µg/l
Ni	40 µg/l
Hg	1 µg/l
Zn	300 µg/l
chloride	250 mg/l
sulfate	600 mg/l
cyanide	0.02 mg/l

⁹ The threshold for sulphate is not based on toxicity, but on its corrosion potential against concrete.

Bottom ashes from municipal waste incinerators, which meets these values may be used in

1.7.2 Fly ash and air pollution control residues

Even though some of the above mentioned applications (cement additive, fill material etc.) have also been tested and suggested as potential reuse option for fly ash, these residues are to be classified as hazardous wastes due to their high concentrations of mobile HMs, POPs and soluble salts. Therefore they are not suitable for any sort of recovery. In many cases, disposal is only permitted in special landfills, underground dumps or special areas of conventional landfills. Before disposal these residues have to be treated in a way that all harmful components are immobilised.

Gypsum from flue gas treatment would theoretically have a market. Its quality is basically comparable to that of gypsum from flue gas treatment in brown-coal power plants. However there is some concern about its Hg-content and again the necessary public acceptance is not given.

1.7.3 Concerns of incinerator ash reuse

Show, Tay and Cheong (2000) summarise the following main areas of concern connected with incinerator ash reuse:

Environmental concerns:

- Leaching: Compounds in incinerator ash may be susceptible to leaching and thus cause storm and ground water contamination.
- Handling and processing procedure: Handling and processing procedures are important but these procedures are not fully developed for incinerator ash. The ash could be hazardous and could pose health related risks to workers in handling the material, as well as local soil contamination.
- Long term effects: The long term effects of incorporating incinerator ash is not fully known and need to be assessed. Long term environmental testing needs to be conducted before full-scale ash reuse is allowed to protect human health and environment.

Engineering concerns:

- Properties of products incorporating incinerator ash: Since the incinerator ash will replace or modify the properties of the products or structures, it will affect the engineering properties (such as strength and durability). Therefore, the materials containing the ash must be re-evaluated thoroughly and carefully both in the laboratory and in the field. The long term physical integrity and behaviour of stabilised ash products need to be assessed.
- Impact of production: Incorporation of the ash may require a change in the material production equipment and/or processes and therefore, the production is likely to be affected.
- Variability in quality: It is important to characterise the properties of incinerator ash and evaluate their suitability before utilising them in civil engineering applications. The ash is difficult to characterise, because it reflects different types and sizes of facilities, unknown sample sizes at each facility, inter-laboratory variation in testing procedures and variable inputs into the ash itself

Economic concerns

- Price: There are no standards specifications to measure the quality of incinerator ash. Requiring incinerator ash to meet the strict specifications of its competing materials, such as Portland cement, may create the perception that there is inconsistent ash quality and

thus quantity, and that prices for “spec” ash are higher than the cost of competing materials. In reality and if allowed and mandated by environmental authorities, there is a vast supply of incinerator ash available at reasonable or subsidised rates from the utilities. However, mandated use of incinerator ash is likely to raise the price of the products.

- Quantity: The quantity available at one location must be large enough to justify the development of handling, processing and transportation systems. The transportation distances involved must be reasonable in terms of competition with conventional materials.
- Life cycle costs: Life cycle costs need to be evaluated for the materials containing incinerator ash. It is possible that the ash may not affect the initial engineering properties but may reduce its service life.
- Disposal costs: If the materials containing incinerator ash cannot be recycled, the disposal costs need to be determined.
- Salvage values: Salvage values of the products containing incinerator ash are not known.
- Lack of incentive: At the present time there is a lack of monetary incentives and also public acceptance to use incinerator ash in civil engineering.

In summary there are two general themes that are prominent when viewing the concerns discussed above. The first is that incinerator ash is perceived as being non-competitive with natural materials, most likely because there is inconsistent ash quality and quantity. The second theme is that there is a “knowledge deficiency” associated with ash reuse, such as a lack of data on environmental and health effects, lack of physical/engineering data, and a lack of familiarity with potential ash applications. Overcoming this constraint through education could lead to the development of regulations by environmental authorities that specifically address the use of incinerator ash in civil engineering applications.

1.7.4 Disposal of bottom ash, dusts and reaction products

Three different ways of residue disposal can be distinguished:

- Disposal in landfills
- Underground disposal (registration and deposition, after packing in big bags)
- Dilution

Dilution is characterised by the distribution of small quantities of residues enriched with high concentrations of pollutants in large quantities of barely polluted material. Dispersed material of that kind is often used as filling material for road surfaces (bitumen) or as additive to cement or concrete. These re-use options for residues have already been discussed in the previous section, however, they should rather be seen as another form of disposal in diluted than a treatment option.

The major potential environmental impacts of concern in connection with disposal of incinerator residues are those associated with the formation and release of leachate and fugitive dust emissions. Fugitive dust emissions generally only occur during the relatively short period of actual deposition in a landfill. The formation of leachate in contrast may constitute both a short and long-term problem¹⁰, which should be minimised through the application of a proper disposal strategy, and through appropriate design and operation of the landfill (IAWG, 1997).

A disposal strategy should observe the following principles (IAWG, 1997):

¹⁰ In this context “short term” may cover a time period of 25 to 50 or 100 years, “long-term” consequently represents the following several hundred to thousands of years.

- Landfills should be designed to minimise the required lifetime of active environmental protection systems (i.e. systems requiring operation or maintenance)
- Any disposal strategy should consider the intrinsic properties of waste and the potential health risks associated with a given disposal strategy
- Landfill design, operation and siting should be adapted to the admitted waste in such a manner that long-term emissions of leachate and gas become or remain environmentally acceptable.
- Any strategy for waste disposal at a landfill site must include consideration of the ultimate fate of the leachate and the residues remaining in the disposal site, as well as derived effects of disposal and leachate management.

Some of the specific strategies which may be relevant to the disposal of incinerator residues include total containment (dry storage), containment and collection of leachate, controlled contaminant release, and unrestricted contaminant release. A detailed discussion of disposal methods however is beyond the scope of this treatise.

The following table gives an overview of MSW incinerator residue disposal practices in various countries (IAWG, 1997):

Table 13: Disposal practices for incinerator residues

Disposal strategy	Bottom ash	APC residues	Combined ash
Total containment	Germany	Canada Denmark The Netherlands Germany	US
Containment and leachate collection	Denmark France Germany Sweden Switzerland The Netherlands	Denmark France Germany Sweden Switzerland	US
Controlled contaminant release	Sweden Denmark	Sweden	
Unrestricted contaminant release	Canada		

In Austria fly ash and air pollution control residues are being disposed of under controlled conditions. Also bottom ash should not be re-used in Austria due to its high content of leachable HMs.

The following Table offers a summary of disposal options and recommendations for incinerator residues:

Table 14: Summary of disposal options

Disposal strategy	Bottom ash	APC residues	Combined ash
Total containment	No	Possibly (e.g. salt mines)	No
Containment and leachate collection	Yes (a)	Yes (a)	Yes (a)
Controlled contaminant release	Yes (b)	Maybe (b)	Maybe (b)

Disposal strategy	Bottom ash	APC residues	Combined ash
Unrestricted contaminant release	No (c)	No (c)	No (c)

(a): If requirements for controlled contaminant release are not met.

(b): If requirements are met. May require prior or in-situ treatment of the residues or may be second stage of disposal.

(c): Only after final storage quality criteria are met.

The filling of void volumes in mines with residues does theoretically not present a re-use method. If packing of the mine is necessary however to avoid potential hazards such as subsidence or break-down of mines, packing of the mine with incinerator residues could be interpreted as re-use. It has to be emphasised that this is a question of interpretation and the disposed (or re-used) residues will not be accessible for later treatment.

Packing can be necessary in coal, salt, ore, and gypsum mines to name but a few. The two

It is generally very important to distinguish between proper treatment allowing sensible re-use of a substance or material, and a quasi-recovery intending only to avoid disposal costs (landfill tax).

1.8 Evaluation of the questionnaires

In order to enable the creation of a database on the management of waste incinerator residues in the various countries, questionnaires have been sent to all UN/ECE-countries.

The questionnaire asked for the number of waste incinerators and their capacity, the input materials, residue generation and characteristics and for treatment technologies used for the individual residues.

The following Table provides an overview of the answers given in the received questionnaires. Estimates are marked with an asterisk.

Table 15: Evaluation of questionnaires

Country	Number of waste incinerators	Waste input	Residue generation	Treatment technologies
Austria	4 municipal 1 hazardous	700 000 t/a 285 000 t/a	BA ¹¹ : 161 000 t/a BA(haz.): 15 600 t/a	BA: solidification + landfill (mun. + haz.)
			FA ¹² : 15 000 t/a FA(haz.): 17 400 t/a	FA: solidification + landfill (mun. + haz.)
			APC ¹³ : 980 t/a FA(haz.): 1 600 t/a	
Belarus	0			
Canada	21 municipal 5 hazardous	886 000 t/a 109 000 t/a	BA: 177 000 t/a*	BA: landfill
				FA: landfill
				APC: landfill
Croatia	1 industrial (testing)	2500 t/a	BA: 85 t/a	BA: landfill
			FA: 7 t/a	FA: export
			APC: 65 t/a	APC: export
Czech Republic	3 municipal 85 hazardous			BA: recycling, export
Cyprus	5 clinical	750 t/a	BA: 130 t/a	BA: landfill
Germany	60 municipal 30 hazardous 23 sewage sludge	1 400 000 t/a 1 000 000 t/a 610 000 t/a	BA: 3 500 000 t/a	BA: recycling, landfill
			FA: 420 000 t/a	FA: recycling (mining), landfill
			APC: 350 000 t/a	APC: recycling (mining), landfill

11 BA = Bottom Ash

12 FA = Fly Ash

13 APC = Air Pollution Control Residues

Country	Number of waste incinerators	Waste input	Residue generation	Treatment technologies
Hungary	1 municipal 64 hazardous	356 300 t/a	BA + FA + APC: 131 300 t/a	
Moldova	0			
Slovakia	2 municipal 37 industrial 39 clinical	119 800 t/a 200 300 t/a (clin. + others)	BA + FA + APC: 65 700 t/a	BA: landfill
				FA: landfill
				APC: landfill
Slovenia	0 municipal 3 hazardous 2 clinical	0 t/a 12 700 t/a 300 t/a	BA: 630 t/a	BA: landfill
			FA: 0 t/a	
			Filter cake: < 10 t/a	APC: landfill
Sweden	22	2 041 000 t/a	BA: 380 000 t/a	BA: landfill
			FA+APC: 83 000 t/a	FA+APC: landfill (30 % FA pre-treated)

In order to accomplish the data gained from the questionnaires data from the EAA Dobris Assessment, 1995 and the OECD Environmental Data 1997 on waste accumulation and incineration in the relevant countries were assembled. They are presented in the following Table:

Table 16: Waste accumulation (1997) and incineration (1995) in Europe

Country	Total waste generated (t/a) (latest available year) OECD, 1997	Incineration plants Dobris Report, 1995	
		Total number	Total capacity
Austria	39.000.000 t/a	4	370.000 t/a
Belgium		9	
Czech Republic	48.120.000 t/a		
Denmark	10.500.000 t/a		
Estonia		2	1000 t/a
Finland	61.000.000 t/a	2	150.000 t/a
France		306	8.700.000 t/a
Germany	265.993.000 t/a	162	
Greece		1	

Country	Total waste generated (t/a) (latest available year) OECD, 1997	Incineration plants Dobris Report, 1995	
		Total number	Total capacity
Hungary	68.000.000 t/a		
Iceland	183.000 t/a		
Ireland	40.300.000 t/a		
Italy		204	1.912.000 t/a
Luxemburg		1	150.000 t/a
The Netherlands	44.955.000 t/a	8	2.850.000 t/a
Norway		50	
Poland	134.014.000 t/a		
Russian Federation		7	757.000 t/a
Spain		17	606.000 t/a
Sweden	91.791.000 t/a	23	1.800.000 t/a
Switzerland	6.750.000 t/a	31	2.300.000 t/a
Slovakia	27.500.000 t/a		
Ukraine		3	880.000 t/a
UK	404.000.000 t/a	212	

Since data on total waste generation were not available for many countries, the following table summarises data on the accumulation of municipal and hazardous waste - waste groups that are well analysed in most countries. The data were again taken from the OECD Environmental Data 1997.

Table 17: Accumulation of municipal and hazardous waste in 1997

Country	Municipal waste generation (1000 t/a)	Incineration of municipal waste (1000 t/a)	Hazardous waste generation (1000 t/a)	Thermal treatment of hazardous waste (1000 t/a)
Canada	18.110	1.200	5.896	225
USA	189.696	29.484	277.337	212.796
Austria	3.841	410	550	190
Belgium	4.781	499	776	64
Czech Republic	2.390	2	1.867	81
Denmark	2.788	1.466	250	92
Finland	2.100	50	559	44
France	28.000	9.759	7.000	1.558
Germany	25.777	6.429		
Greece	3.200	1		
Hungary	4.300	300	3.537	1.517

Country	Municipal waste generation (1000 t/a)	Incineration of municipal waste (1000 t/a)	Hazardous waste generation (1000 t/a)	Thermal treatment of hazardous waste (1000 t/a)
Iceland	149	30	6	5
Ireland	1.550		248	50
Italy	27.000	1.400	2.708	112
Luxembourg	218	126		
Netherlands	8.956	2.192	1.520	160
Norway	2.637	448	500	29
Poland	11.352	1		
Portugal	3.500		1.365	10
Spain	14.296	625		
Sweden	3.900	1.300		
Switzerland	2.660	2.040	854	289
Turkey	22.315	515		
UK	20.000	2.500	1.844	197
Slovakia	1.620		1.347	167

The OECD Environmental Data 1997 did not provide data for a fixed reference year, but for the latest year, when data were available, generally between 1990-1995. Evaluating these data, it has to be taken into account that the generated waste streams are growing still quickly in most countries, and that also the percentage of incineration is rising in some countries, due to increasingly strict regulations or even bans on the disposal of untreated waste.

Using the ranges of incinerator residues generated from 1 t of waste that have been presented in Chapter 1.5, ranges of generated residues could be estimated from the data presented above. However, the results would be subject to the uncertainties mentioned above.

Details on the treatment methods used in selected countries have been presented in Chapter 1.7 based on data of the IAWG 1997.

Obviously recent and consistent data of the individual countries would reflect the situation of incinerator residue management the UN/ECE much better than estimates based on not quite recent data assembled from various data sources and various reference years. The data situation in the EU might improve in the future, since the EAA (European Topic Centre on Waste) is about to set-up a database on waste treatment plants in the EU countries.

1.9 Conclusions and Recommendations

1.9.1 Conclusions

- It is state-of-the-art to recover ferrous metals from the bottom ash.¹⁴
- Under certain circumstances the remaining bottom ash could be used for various applications, such as road aggregates, filling material, admixture in soil stabilisation, masonry bricks, cement replacement material, daily cover in landfills, wind and sound barriers or as dams in areas of suitable hydrology.
- In any case the bottom ash has to be stabilised in an ageing process before use. The surface has to be covered with a layer of very low permeability.
- Fly ash and air pollution control residues are to be classified as hazardous waste due to their high concentrations of mobile HMs and POPs;
- In general they are not suitable for any sort of recovery; In any case long term environmental testing has to be conducted before full-scale fly ash or air pollution control residue reuse is allowed, to protect human health and environment
- Before disposal fly ash and air pollution control residues have to be treated in a way that all harmful components are immobilised.
- The packing of void volumes in mines is sometimes interpreted as recovery, if it can be argued that it is necessary to avoid potential hazards such as subsidence or break-down of a mine. It has to be emphasised that this is a question of interpretation and the residues will not be accessible for later treatment, which is a prerequisite for recovery.
- The choice of a treatment option is very much dependent on the quality of the residues and the intention of its future use.
- It is important that a treatment option is chosen on the basis of the envisaged environmental goal and reasonable costs for the aspired operation (Schaub, 1996).
- The results of the questionnaires and the data search in literature suggest the following conclusions:
- Landfilling of waste is generally still the most common way of waste management, rather than waste incineration or other treatment options.
- In a number of countries (especially in Eastern Europe) there is either no waste incineration capacity or it is only carried out on a small scale.
- Only small amounts of residues are produced, but due to lack of data, it is not possible to access whether these residues cause any problems.
- Landfilling of incinerator residues is the most common method of residue management in many countries, often directly without pre-treatment. Residues that are exported most probably share the fate of being landfilled elsewhere.
- In some cases there is not sufficient awareness of the problems caused by the high concentrations of heavy metals, persistent organic pollutants and soluble salts in the respective residues. These pollutants pose a considerable threat to the surrounding environment, esp. groundwater.
- If countries are aware of the problem, it is often not reflected in the form of collection and analysis of national data on residue management. This lack of sensible data management on a national basis leads in consequence to a lack of data on international level.

¹⁴ Also the recovery of non-ferrous metals is possible by using the eddy-current process

1.9.2 Recommendations

- Waste prevention should have priority over waste reuse, recycling and disposal.
- Processes should be developed that produce as small amounts of residues as possible with better material properties in energy efficient processes.
- Research would be necessary to develop even better treatment techniques for residues to obtain materials with improved inert qualities for disposal.
- Waste incinerators and facilities for treatment of residues should be equipped with state of the art technologies (according to Annex III of the HM Protocol and to Annex V of the POP Protocol: fabric filters in combination with dry or wet methods for controlling volatiles, SCR or SNCR and adsorption with activated carbon or coke) to minimise emissions of dioxins and furans ($< 0.1 \text{ ng I-TEQ/Nm}^3$), dust and heavy metal emissions.
- Long term environmental testing needs to be conducted before full-scale ash reuse is allowed, to protect human health and environment.
- The residue-problem should be tackled starting from the waste input.
- All waste management options (waste incineration, co-incineration, mechano-biological treatment, composting, recovery, disposal etc.) should be analysed and compared considering individual residues and their pathways.
- A discussion of residues from waste incineration is never complete without a thorough comparison of all other methods of waste management and the management of their residues.
- Combustible waste should be minimised as much as possible.
- Disposal of filter dust and air pollution control residues should only be permitted in special landfills, underground dumps or special areas of conventional landfill.

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