

CHAPTER 4: OVERVIEW OF TECHNOLOGIES USED FOR ENERGY RECOVERY

This chapter presents a short overview of established technologies for integrating energy recovery into solid waste management systems. It includes a description of alternative and emerging technologies based on gasification or pyrolysis of waste.

The fundamentals of the technologies are briefly described including - where available - flow diagrams, mass and energy balances, eventual pre-treatment necessities, and residue qualities. For some technologies typical plant designs are presented.

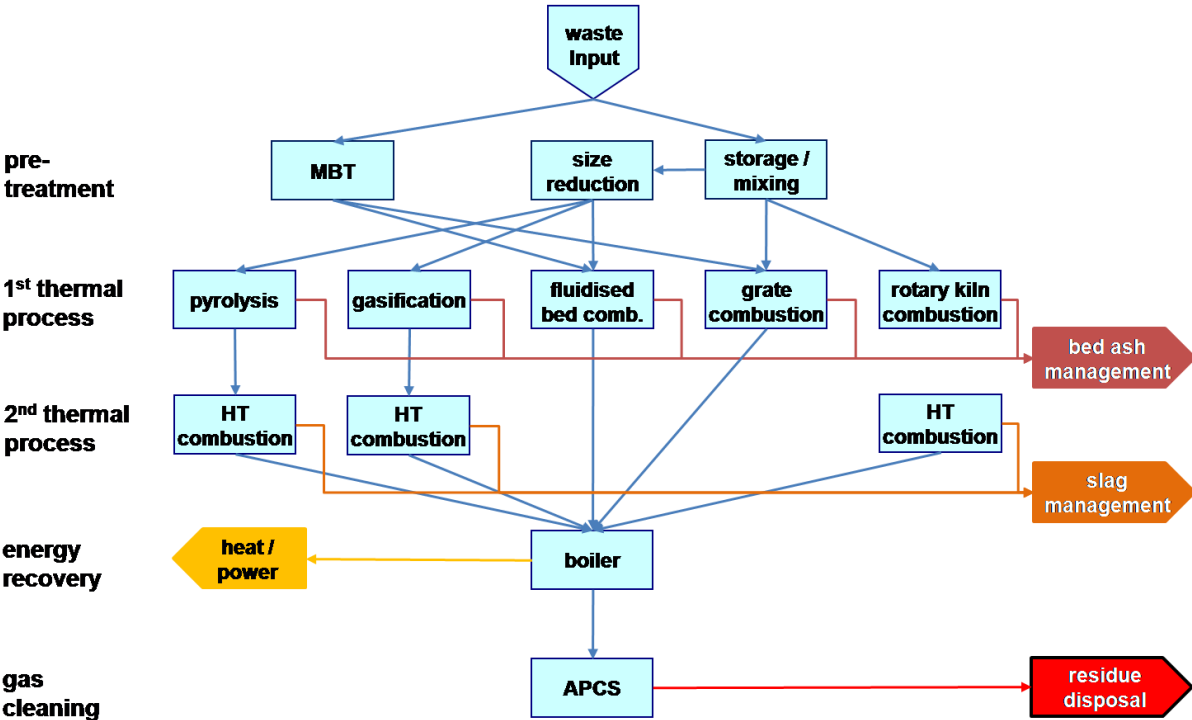
The technologies examined are:

- grate incineration;
- fluidised bed incineration;
- rotary and oscillating kilns;
- options for mechanical and biological treatment (MBT);
- gasification;
- pyrolysis.

Gasification and pyrolysis of waste and waste derived fuels are in principal designed as at least two-stage processes with a direct combustion of the process products.

Figure 1 illustrates the various options for energy recovery from waste. Some options (combustion in grate systems and rotary kilns) process waste without pre-treatment, whereas other options, especially fluidised bed combustion, and (in most cases) gasification and pyrolysis, require size reduction combined with removal of metallic species.

Figure 1: Various common configurations for energy from waste plants (HT: high temperature; APCS: air pollution control system)



Solid recovered fuel (SRF) from MBT plants is typically either used as co-combustion fuel in cement kilns or coal fired power plants or burnt in fluidised bed or grate furnaces. Residues from MBT and sorting plants end up in grate furnaces.

Figure 1 also shows that all of the listed processes contain a heat recovery boiler and, in many process chains, rather complex air pollution control (APC) systems. Since these stages do not depend on the front-end thermal process, they are more or less equal for all applications and are described in a separate section (below). The same applies to storage, mixing, size reduction and metal scrap separation facilities.

One important issue for energy from waste (EfW) systems is the quality and management of process residues. This is true for residues such as bed ashes and slags from high temperature combustion, but is a particular issue for APC residues. The first mentioned residues may have some utilisation potential, but APC residues are characterised by high levels of pollutants and require treatment and/or specialised disposal.

The figures and statistics provided here are based on operational processes and collated from data sets relating to 2006 or 2007 - unless otherwise stated.

In addition, the Task also attended a study tour of Japanese waste management plants in November 2009. A summary of this study tour and data on the plants visited is available in Appendix 2: Study tour of Japan.

Pre-treatment stages of EfW technologies

As mentioned above, many EfW plants use process stages which are independent of the thermal process. The first of these stages is the storage and pre-treatment of the feedstock. Pre-treatment systems are required to ensure that the waste is in an appropriate form for the combustion process.

There are a number of commonalities in pre-processing, including removal of bulky items; mixing of the waste to homogenise the composition and the calorific value of the material; and size reduction where necessary. These processes take place at the front end of the plant, often within a reception hall or waste bunker. Figure 2 shows a typical reception hall of a waste incinerator.

Figure 2: Waste reception hall of the Dutch Alkmaar incinerator



For combustion in grate furnaces, waste pre-treatment is (in principle) not needed. That is why grate incinerators are often referred to as 'mass burn' facilities. In reality, however, the bunker of such facilities is often equipped with a rotary shear for crushing bulky material. Furthermore, the crane operator mixes the waste in the bunker to achieve a more homogenised feedstock for the combustion chamber.

The waste reception area includes a bunker, which has the dual function of providing temporary storage and protecting the surroundings from odours. This area is kept under negative pressure (to ensure odours remain within the building). Cranes are used to mix the waste in the bunker and to fill it into the feeding chutes of the incinerator (see Figure 3).

Figure 3: Waste bunker with two cranes mixing the waste (left) and filling the feeding hopper with a crane load of waste (right)



In contrast, fluidised bed (FB) incinerators need fuel of limited particle size; for stationary or bubbling bed furnaces the preferred particle size is < 50 mm, for circulating ones < 25 mm; revolving FBs are more flexible and can cope with material of up to 200 mm.

Hence for these plants more effort has to be spent in the pre-treatment of the waste fuel. This starts with sorting and removal of bulky and metallic items. The latter is done by magnetic separation for ferrous and, to an increasing degree, also by eddy current systems for non-ferrous scrap removal. This procedure is mainly followed by crushing and/or shredding.

A more complex and also more expensive pre-treatment of waste for FB combustion comprises an MBT plant which produces SRF as a fluffy or pelletized material. This fuel is also used for combustion in dedicated power plants or as co-combustion fuel in coal fired power plants, cement kilns and other industrial furnaces. The methods applied involve sorting, sieving, crushing or shredding and eventually moulding.

Rotary kiln plants are mainly used for treatment of industrial and hazardous waste. These facilities are relatively flexible and can take solid, liquid, pasty, sludgy, and gaseous waste. A speciality is the combustion of hazardous waste 'drummed' in containers such as 200 l barrels. The type and variety of accepted waste often requires complex storage in different forms, ranging from bunkers to tank farms and sealed bunkers with the capability to make the waste inert. The actual fuel mixture has to be composed based on good knowledge of composition and calorific value of the various waste types.

Thermal processes

Overview

The thermal processes applied for energy recovery from waste are combustion, gasification and pyrolysis. Their principal distinguishing feature is the oxygen content in the process atmosphere; furthermore, the processes are operated in different temperature ranges.

Pyrolysis is an endothermic process, always performed under strictly inert atmosphere without access for any oxidising agent. The effect is thermal degradation and fragmentation of organic constituents. Gasification (also endothermic) is a sub-stoichiometric oxidation process, whilst combustion is the total oxidation of the fuel.

Table 1 summarises some of the typical process parameters for pyrolysis, gasification and combustion processes.

Table 1: Typical operation parameters and reaction products of thermal waste treatment processes

	Pyrolysis	Gasification	Combustion
Temperature / °C	250 - 700	800 - 1,400	850 - 1,400
Pressure / bar	1	1 - 50	1
Atmosphere	Inert / N ₂	O ₂ , H ₂ O, air	air, O ₂
Stoichiometry	0	< 1	≥ 1
Gaseous products	H ₂ , CO, C _n H _m	H ₂ , CO, CH ₄ , CO ₂	CO ₂ , H ₂ O
Solid products	Ash, coke	Slag	Ash/slag

Pyrolysis and gasification for energy recovery from waste are, in most cases, followed by immediate combustion of their gaseous – and in the case of pyrolysis, also solid – reaction products. Such processes (at full scale) have mainly entered the market in Japan. Their characteristics are described in more detail below.

Pyrolysis

Pyrolysis is the thermal decomposition or fragmentation of organic matter in a strictly inert atmosphere. The reaction starts at 200 - 250°C and is, in this region, often called degassing - at high temperature the terms carbonisation or coking are also common. The highest temperature in these processes is in the order of 700°C.

The main pyrolysis reactions in the various temperature ranges are listed in Table 2.

Table 2: Main pyrolysis reactions as a function of temperature [Lenz 1979]

T in °C	Reactions
100 - 120	Drying
250	Split off: H ₂ O, CO ₂ , H ₂ S, HCl
340	Destruction of aliphatic bonds, split off: CH ₄ , aliphatics
380	Formation of pyrolysis coke
400	Splitting of C-O and C-N bonds
400 - 600	Transformation of bitumen to pyrolysis oil and tar
600	Cracking of long-chain compounds, formation of aromatics
>600	Formation of butadien, cyclohexane, benzene, PAH

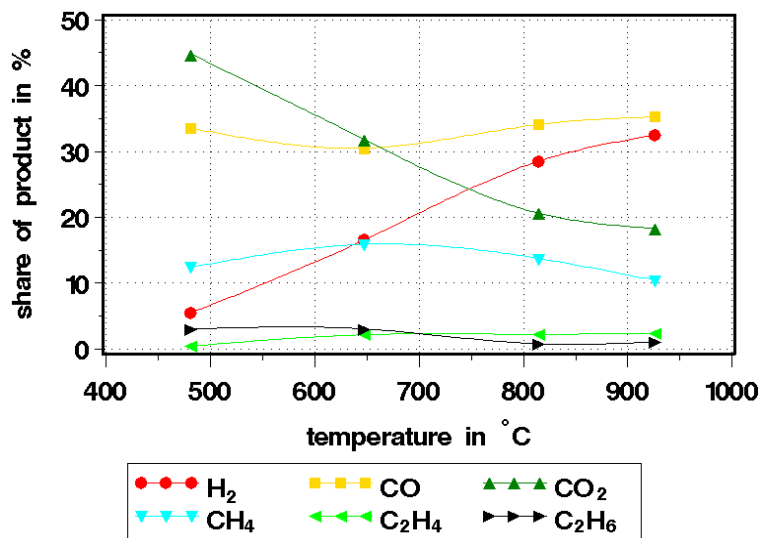
Products of pyrolysis of waste are:

- gases, predominantly CO, H₂ and short chain hydrocarbons;
- so-called pyrolysis oil comprising low volatile hydrocarbons up to tars;
- solids, which are a mixture of coke and inert ashes.

The proportion of gaseous, liquid and solid products will depend on the reaction temperature. The amount of gaseous products increases slightly with the temperature, whereas the share of solid residues decreases.

The gas phase composition is a function of the reaction temperature, too. Figure 4 shows the influence of temperature on the distribution of gaseous pyrolysis products as obtained in experiments with waste mixtures [Lenz 1979]. It is evident that with increasing temperature, the yield of H₂ increases and that of CO₂ goes down. Methane has its highest concentration at about 650°C.

Figure 4: Share of major gaseous pyrolysis products as a function of reaction temperature (adopted from [Lenz 1979])



Typical concentration ranges and mean mass flows in the gas from waste pyrolysis in the temperature regime of 600 - 650°C are compiled in Table 3. The dust content is missing; it depends on the type of pyrolysis process and the turbulence in the gas phase.

Table 3: Pyrolysis gas concentration ranges and mean mass flows per Mg of waste in the temperature range 600 - 650°C (adopted from [Bilitewski 1985, Fichtel 1987])

	Concentration [mg/m ³]	Mass flow [kg/Mg]		Concentration [mg/m ³]	Mass flow [kg/Mg]
CO ₂	150,000 - 250,000	90	NH ₃	20 - 100	0.03
CO	70,000 - 120,000	45	HCN	1 - 50	0.01
H ₂	4,000 - 6,000	2.5	CH ₄	30,000 - 40,000	18
SO ₂	<100	<0.05	C ₂ H ₄	10,000 - 15,000	6
H ₂ S	1,000	>0.5	C ₂ H ₆	14,000 - 18,000	8
COS	Traces		C _n H _m	Traces	

The table indicates that pyrolysis gas has a rather complex composition and direct use requires extensive gas cleaning, which is especially difficult for the removal of sulphur

compounds and sticky dust particles or tar. This is the reason why pyrolysis application in waste treatment is realised with direct combustion of the gas phase without major prior cleaning.

The advantage of such processes is the good quality of the metal scrap in the solid pyrolysis residues which have - due to the absence of oxygen - clean metallic surfaces.

Gasification

Gasification is the partial oxidation of organic substances using oxygen, air, or steam as oxidising agents. The reaction product, called synthesis gas (or syngas), consists mainly of H₂ and CO with small amounts of methane and other short chain hydrocarbons. The reaction is endothermic. It is called autothermic if the energy needed for the reaction is supplied by sub-stoichiometric combustion of the organic substance. If the reactor is externally heated, the gasification is called allothermic. The solid residues are inert ashes or slags and fly ashes.

As with pyrolysis, gasification of MSW is in most cases also followed by combustion of the gas in a combustion chamber. Only the Schwarze Pumpe and the Thermoselect processes have implemented gas cleaning for use of the gas in a gas engine. The first German Thermoselect plant (now shut down) however, burnt the cleaned gas in a combustion chamber.

Table 4 shows analytical data measured in the synthesis gas of the Thermoselect process at a gasification temperature of approx. 1,200°C.

Table 4: Synthesis gas concentration ranges and mean mass flows per Mg of waste analysed in the Thermoselect process (*: ng(I-TEQ)/m³, **: mg(I-TEQ)/Mg, [Stahlberg 1995])

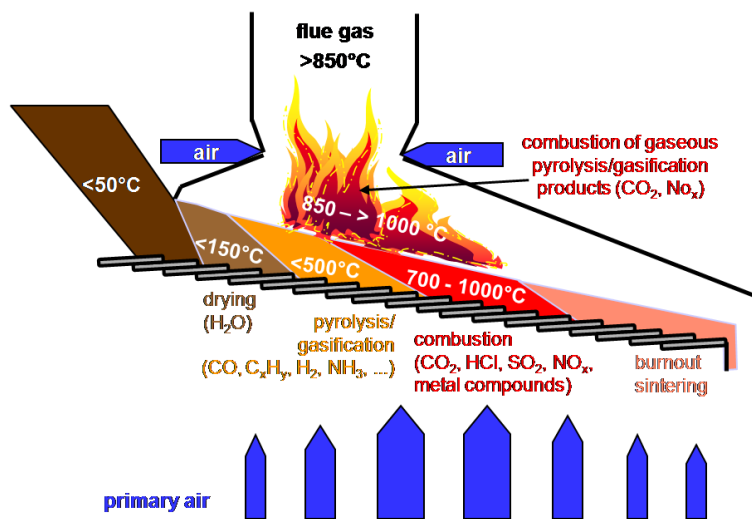
	Concentration [mg/m ³]	Mass flow [kg/Mg]		Concentration [mg/m ³]	Mass flow [kg/Mg]
O ₂	<1,000	<1	SO ₂	800 - 3,000	1.5
CO ₂	400,000 - 500,000	410	HCN	1 - 10	<0.01
CO	400,000 - 450,000	420	N ₂	20,000 - 25,000	25
H ₂	22,000 - 30,000	27	CH ₄	<0.5	<0.0005
HCl	100 - 300	0.3	C _n H _m	<0.1	<0.0001
H ₂ S	600 - 1,500	0.9	PCDD/F	<0.05*	<0.05**

Combustion

Combustion is the total oxidation of a fuel, predominantly of its organic components, but also of some inorganic ingredients like elementary sulphur. The process is exothermic with the main energy releasing chemical reactions:



Figure 5: Principal processes inside the combustion chamber of a grate furnace



In reality, combustion is the final stage in the chain of chemical reactions which take place between the entry of the waste into the combustion chamber at ambient temperature and its final combustion temperature in the range of 800 to $> 1,000^\circ\text{C}$.

The process can best be explained by examination of the combustion of waste in grate furnaces, where the fuel forms a bed on top of the grate and the combustion air is injected through the grate. The different local temperatures and oxygen concentrations cause a succession of reactions from drying through pyrolysis and gasification to final combustion. A schematic of this reaction chain is depicted in Figure 5.

The same processes take place in all combustion facilities, although the local distribution and the time scales differ. In fluidised beds, for example, the described processes are rather fast following each other around a single grain of the fuel in the continuum of the sand bed; the final gas burnout takes place in the freeboard.

Typical composition data for flue gas from waste incineration are listed in Table 5. The table has been compiled for grate furnace systems with an air consumption of $4,500 \text{ m}^3$. Fluidised bed systems may be operated at lower air supply which would increase the concentration of the gaseous species. The fly ash or dust concentration can be much higher, particularly in stationary or bubbling beds, since the bed material will to a certain extent also be transferred into the flue gas stream.

Table 5: Raw gas concentration ranges and mean mass flows per Mg of combusted waste (*: ng (I-TEQ)/m^3 , **: mg(I-TEQ)/Mg , [IAWG 1997])

	Concentration (mg/m^3)	Mass flow (kg/Mg)		Concentration (mg/m^3)	Mass flow (kg/Mg)
O_2	60,000 - 120,000	500	NO	100 - 500	2
CO_2	150,000 - 200,000	900	NH_3	5 - 30	0.1
H_2O	110,000 - 150,000	600	CO	$< 10 - 30$	0.1
dust	1,000 - 5,000	20	TOC	1 - 10	0.02
HCl	500 - 2,000	6.5	Hg	0.1 - 0.5	0.002
SO_2	150 - 400	2	PCDD/F	0.5 - 5*	$< 5^{**}$

The table indicates the necessity of thorough cleaning before the gas is emitted to the atmosphere.

The solid residues from waste incineration are bottom ashes and fly ashes.

Energy recovery

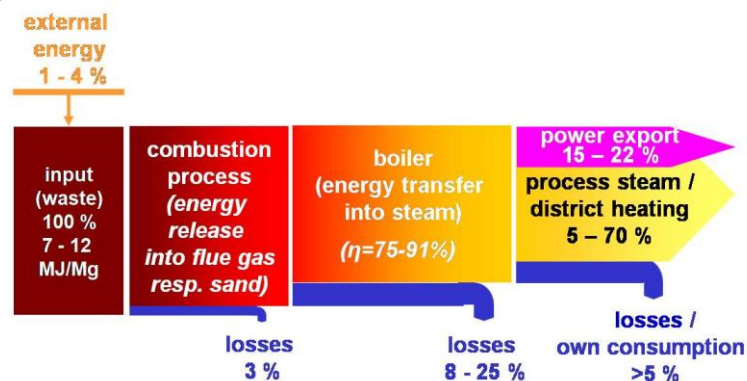
In all modern thermal processes, the chemical energy of the fuel which is finally released into the off-gas of a combustion process is recovered in a boiler. Three alternatives are available for utilisation of the heat:

- direct export as heat for district heating (usually through a so-called 'steam cycle') or as process steam to industry;
- conversion to electricity using turbines;
- both by using heat directly and generating electricity, called combined heat and power (CHP).

A varying part of the generated energy - depending on the process technology - is often used internally in the operation of the plant.

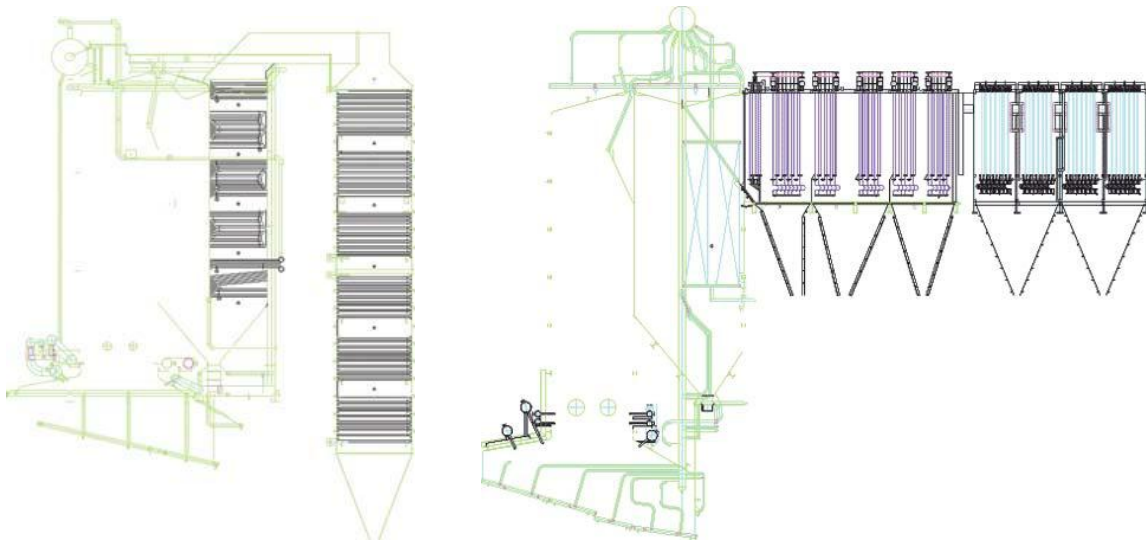
The principles of energy recovery in incineration plants are explained in Figure 6. The scheme is in principle valid for all kinds of combustion plants with heat recovery boiler; i.e. in the context of this report for grate incineration as well as for fluidised bed systems or combustion in combustion chambers.

Figure 6: Energy flow in a waste incineration plant



The design of boilers used in EfW plants is, in principle, the same as in power plants. Schematics of two commonly used configurations, a vertical and a horizontal boiler, are shown in Figure 7.

Figure 7: Vertical (left) and horizontal boiler (right) [Vølund 2006]



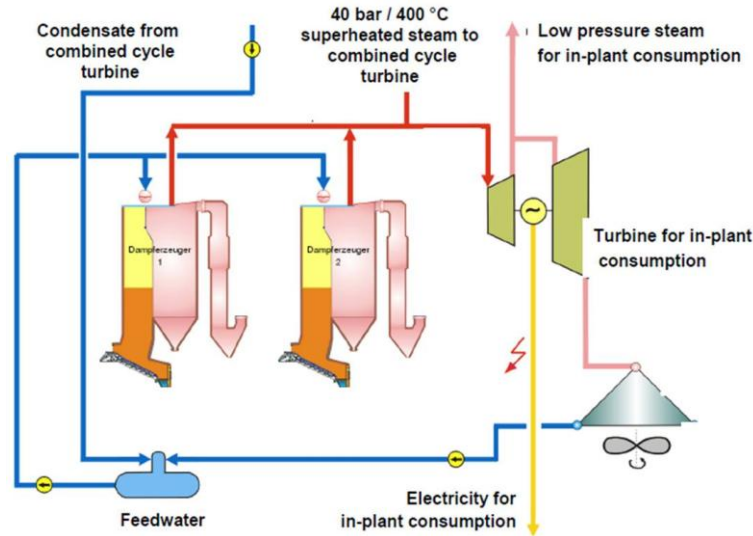
Boilers in modern waste incineration plants of any kind reach a primary efficiency of 85%, some even slightly higher. However, they are operated at lower steam conditions than those in power plants (typically 400°C and 40 bar to avoid corrosion caused by the high Cl inventory of most waste fuels and the resulting high chloride concentration in the ash layers on the boiler tubes). The consequence is a lower power efficiency of about 22 - 25%. Accounting for in-house consumption, the export of power rarely exceeds 21%.

In recent years there has been a growing interest in renewable energy around the world. The drivers for this include the awareness of limited fossil fuel resources and the more and more recognisable effects of global warming. This awareness has pushed energy recovery from thermal waste treatment high up on the agenda, the more so since the biogenic energy inventory in MSW is acknowledged in a number of countries and in some of these even supported by higher power prices.

The first approach for improved power efficiency in waste fired boilers was the application of higher corrosion resistant boiler wall materials, such as Ni-base alloys. This has been demonstrated at facilities at Brescia (Italy) and in the new Amsterdam waste incineration plant. Brescia operates the boiler at 450°C, 450 bar, and reaches an efficiency of 26%; Amsterdam (with 440°C and 130 bar) achieves 30% [Martin 2006; AEB 2006].

Another approach to improving efficiency is the concept of integration of a waste boiler and a combined cycle natural gas turbine, which has been realised in Mainz, Germany. The concept is shown schematically in Figure 8 [Martin 2006]. The achieved power efficiency is $\geq 40\%$.

Figure 8: Combination of EfW and gas turbine (Mainz concept, [Martin 2006])



Air pollution control (APC)

Process Stages

In waste incineration, the removal of pollutants from the flue gas is one of the most important and most expensive process stages. This process is a regulatory requirement since the air emission limits applicable for waste incineration are the most stringent of all the industrial combustion processes. In the EU the Waste Incineration Directive sets the standards in 2000 [European Parliament and Council 2000] and these have been adopted by legal regulations in the member countries. Only few member countries, e.g. The Netherlands and Germany, decided on minor deviations from the directive to even higher standards. Regulations outside the EU are of similar stringency as can be seen in the compilation of selected national air emission standards in Table 6.

Table 6: Air emission limits in the EU, Canada, Japan, and the USA in mg/m³ (PCDD/F in ng(I-TEQ)/m³), daily means of dry gases at 273 K, 101.3 kPa and standardised to the respective O₂ concentration (* : Cd+TI)

	EU	The Netherlands	Germany	Canada	Japan	USA
O ₂ (vol%)	11	11	11	11	12	7
Dust	10	5	10	17	10-50	24
HCl	10	10	10	18	15-50	25
HF	1	1	1			
SO ₂	50	40	50	21	10-30	30
NO _x	200	70	200	110	30-125	150
CO	50	50	10		50	100
Hg	0.05	0.05	0.03	0.057	0.03-0.05	0.03-0.05
Cd	0.05	0.05	0.05*	0.014		0.02
Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V	0.5	0.5	0.5			
TOC	10	10	10			
PCDD/F	0.1	0.1	0.1	0.14	0.5	0.14-0.21

The ranges given in Table 6 for Japan demonstrate that most emission standards are not fixed values, but calculated from the throughput of the plant and its stack height. Such procedures make a lot of sense, since they not only take the concentration of pollutants into account, but also their dispersion.

Flue gas cleaning can be achieved in many ways and is in principle independent of the type of the combustion process. The design of the actual configuration in a specific full scale plant depends not that much on the desired quality of the cleaned gas - which in any case has to comply with about the same emission standards everywhere - but on investment, operation, and maintenance costs. The disposal or eventual utilization options of the APC residues has a high impact as does the (land) space available in case of any future upgrading. Other important factors are administrative regulations like the permit or ban for liquid effluents, and finally even personal preferences of the stakeholders.

This explains why today all technologies and all kinds of combinations of abatement options can be found in full scale installations.

It is common practice to organise the APC systems by installing subsequent process stages to remove the pollutants in the following order:

- fly ash;
- acid gases;
- specific contaminants like Hg or PCDD/F;
- nitrogen oxides.

Significant research activities during the last decade have led to the development of simplified processes which allow the combination of formerly separate gas cleaning processes and contribute to a great improvement of the eco-efficiency of modern waste incineration plants.

The following brief description of the most common gas cleaning options uses information taken mainly from three sources [IAWG 1997, Vehlow 2006, US EPA 2009].

Particle removal

The first step in most APC systems is the fly ash removal which can be done by:

- cyclones;
- electrostatic precipitators (ESP);
- fabric filters or bag houses.

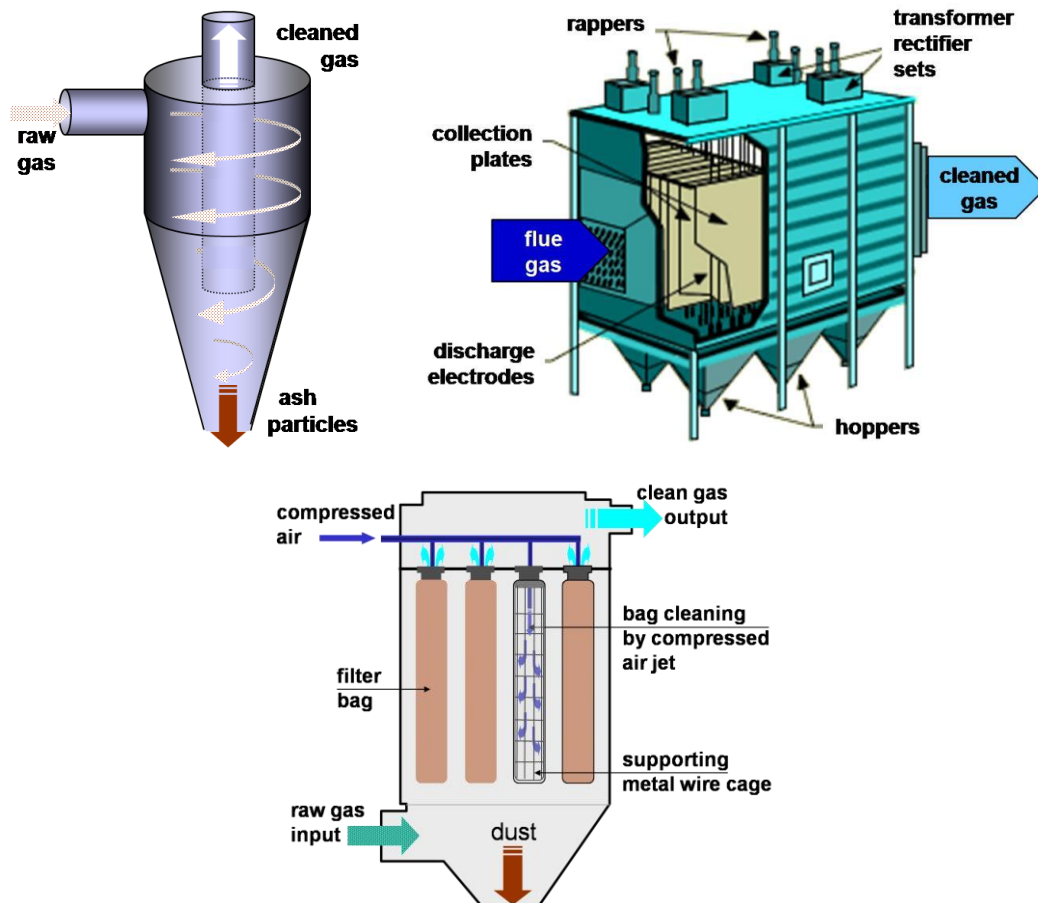
A cyclone uses inertial impaction for fly ash separation. The gas is entering a cylindrical chamber tangentially at high velocity and is forced into a cylindrical path. The centripetal force acting on the particles causes them to collide with the walls where they impinge and settle down into the discharge hopper. The gas is extracted through a central tube. A scheme of a cyclone is shown in the left part of Figure 9. Due to their limited removal efficiency for fine particles, cyclones are not often found in modern plants or they serve for pre-deposition of the coarse fly ash.

In an ESP, the flue gas passes an electric field with spray anodes charging the dust particles and cathodic collection plates where they are deposited. The simple design, low pressure loss and easy operation make ESP the most widely applied option for fly ash separation in waste incineration – as well as in other combustion facilities like coal fired power plants. A scheme of a technical design is shown in the top right part of Figure 9. A modern ESP, which comprises at least two and often three sections, guarantees, dust removal efficiencies

of >99% for particle sizes between 0.01 and >100 μm . Three-field ESP reach clean gas dust levels in the order of 1 mg/m^3 .

In a few installations, wet ESP are implemented at the back end for polishing purposes. In these ESP the collecting plates are cleaned with water instead of rapping. The residues from wet ESP are a sludge or suspension and their disposal may cause specific problems.

Figure 9: Scheme of a cyclone (top left), an ESP (top right), and a bag house filter (bottom)



Fabric filters can achieve even lower emission values than those of ESP. In a fabric filter the raw gas passes fabric bags which are supported by metal cages from the outside to the interior. The fly ash stays on the outer surface of the filter bags and is periodically removed by an air pulse blown into the bag from the interior. This cleaning releases the particles which fall into the discharge hopper. A schematic of a fabric filter is shown in the bottom part of Figure 9. Fabric filters guarantee clean gas dust concentrations in the order of 1 mg/m^3 and below.

Chemical gas cleaning

Primary fly ash deposition in the APC system is usually followed by chemical gas cleaning, which can be performed in two different ways:

- by wet-scrubbing;
- by dry scrubbing.

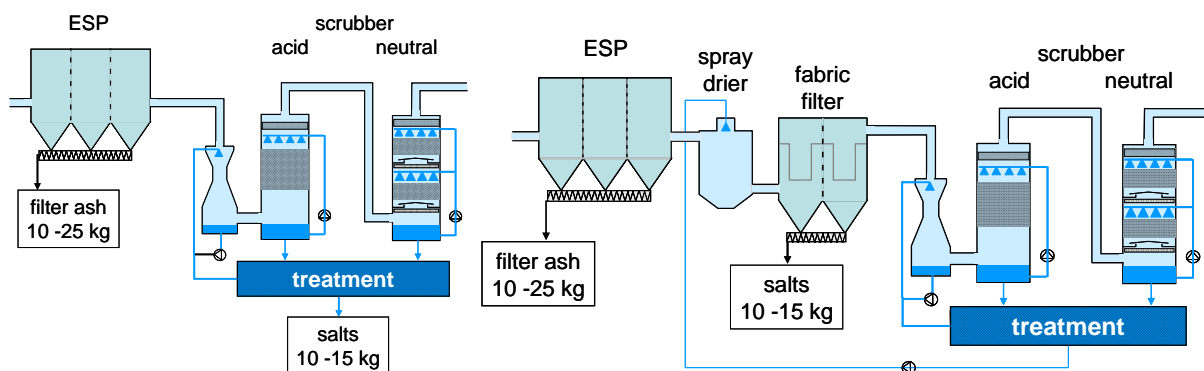
Wet scrubbing

Wet scrubbing is based on the principle of absorption of gaseous components in a liquid. The efficiency of such absorption processes depends on the available surface of the liquid, which controls the mass transfer out of the gas into the liquid phase. Different techniques are used to achieve this goal:

- venturi scrubbers;
- packed towers;
- plate and tray towers;
- film absorbers.

Wet scrubbers operate close to stoichiometry and are common in waste incineration in central Europe. Today's systems are two-stage installations with an initial acid scrubber, followed by a neutral or weakly alkaline one. The acid scrubber is often either a spray or venturi type and reduces the flue gas temperature from 180 - 200°C down to 63 - 65°C. In the second stage packed towers are mainly used. Wet systems are operated with or without discharge of liquid effluents. The latter configuration is currently the preferred approach.

Figure 10: Schemes of wet scrubbing systems with (left) and without (right) liquid effluents



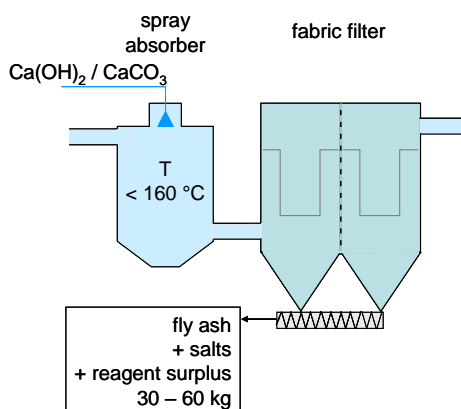
These two-stage systems have very high removal efficiencies for the halogen hydrides HF, HCl, and HBr, for mercury, and for SO₂. For these components, the raw gas concentrations are easily reduced well below the emission standards.

The solid scrubbing residues are removed from the gas flow in a subsequent - in most cases fabric - filter. An alternative way to evaporate the scrubbing solutions is by drying in steam heated devices.

Dry scrubbing

Dry and semi-dry scrubbing processes are simple and cheaper than wet methods, which explains their preferred installation in many plants across the world. In most cases the adsorbent - most common ones being limestone, CaCO₃, calcium oxide, CaO, or lime Ca(OH)₂ - is either injected directly into the gas duct or into a spray dryer downstream of the boiler. This can be done in dry form (dry process) or as a slurry (semi-dry process). A typical configuration of dry scrubbing is shown in Figure 11.

Figure 11: Scheme of a dry scrubbing system



The scrubbing products are in most cases removed from the flue gas by a fabric filter. In some installations, a separation of the fly ashes prior to the spray dryer may be found. For such purpose, cyclones are commonly installed.

The main disadvantage of dry scrubbing systems is the high amount of APC residues produced. Even where these are recycled back into the feed, it is unavoidable that a high surplus of unspent additive remains. This surplus increases if lower emission limits have to be reached.

Another option for dry scrubbing is the NEUTREC[®] process which applies freshly ground NaHCO₃ for neutralisation of acid gases. The gas cleaning products can be treated for utilisation in other processes like metal melting or glass production [Korte 1994]. This process operates close to stoichiometry, like wet systems, so minimising solid APC residues.

NO_x abatement

For the abatement of NO_x two strategies are followed:

- the non-catalytic removal (NSCR) by injection of ammonia or another nitrogen containing compound into the hot flue gas (at about 950°C) in the first flue of the boiler; or
- the selective catalytic reduction (SCR) at a temperature level of 250 to 300°C, in most cases at the end of the gas cleaning system after reheating of the flue gas.

Both strategies allow compliance with the air emission limit of 200 mg/m³ laid down in the Waste Incineration Directive. However, if even lower emission limits are enforced, the SCR may be advantageous.

Residue management

There are three categories of solid residues from EfW facilities:

- bottom or bed ash (largest contributor in terms of weight);
- fly ash (dust);
- APC residues.

Whereas the air emissions from EfW facilities are strongly (and at almost the same standard) regulated all over the world, a similarly common perspective in view of solid residues is missing. There is no uniform understanding of the principles of their disposal, treatment, or utilisation.

The least problematic of these residues are bottom or bed ashes from grate or FB combustion and slags from gasification or high temperature combustion processes. Countries like the Netherlands, Germany and Denmark utilise almost all of these ashes in the building sector, preferentially in road construction. These countries have issued respective regulations and quality standards. The Netherlands even utilise part of the filter ashes. Japan is starting utilisation of vitrified bottom ashes from waste incineration and of molten slags from gasification and high temperature systems. Most countries, however, dispose of the solid residues from EfW processes to landfill.

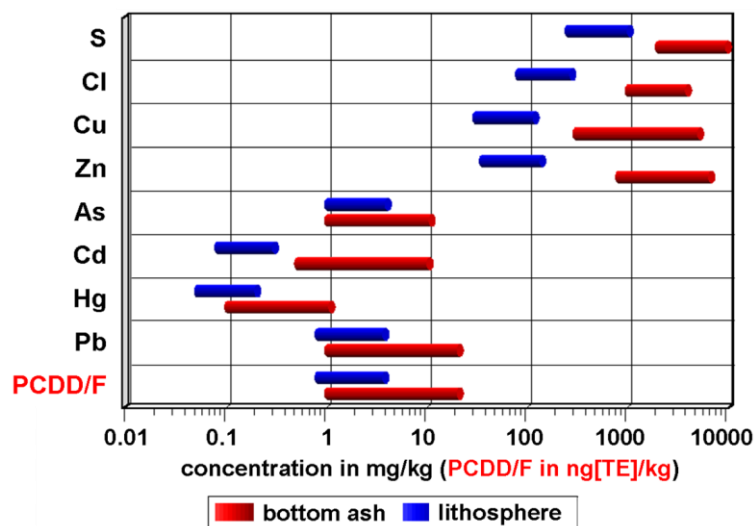
Quality standards have been developed for bottom ashes from waste combustion and are applied in a number of countries to control the access to utilisation options or to different types of landfills.

Fly ash is considered hazardous because of its high inventory of heavy metal compounds and of low volatile organic micro-pollutants such as dioxins. The typical disposal option for these residues is to landfill. This is also the case for APC residues due to their high level of water soluble alkali and alkali earth alkali.

Bottom ashes

Bottom ashes from grate or bed ashes from fluidised bed systems can be characterised as a mixture of silicatic and oxidic phases. The ashes from these plants are sintered, the respective residues from gasification or high temperature combustion are molten and those from pyrolysis contain a significant amount of carbon, the so-called pyrolysis coke.

Figure 12: Concentration ranges of selected elements in grate ash, boiler ash and fly ash (adopted from [IAWG 1997])



The mass and volume reduction of thermal waste treatment causes an enrichment of a number of heavy metals in the bottom ashes. Figure 12 shows concentration ranges of selected metals in MSW bottom ashes and in the earth's crust [IAWG 1997]. With the exception of As and Hg, all heavy metals, even those with a significant volatility in waste incineration like Cd, are highly enriched in the grate ashes compared to the lithosphere. That is why these materials have to be properly assessed when determining their utilisation or disposal option.

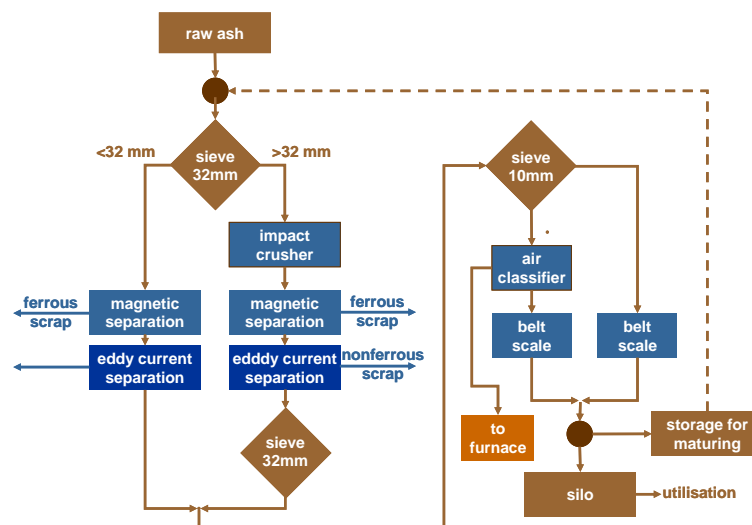
Another important component of the bottom ashes is the salt inventory in the bottom ashes. Since ashes from grates are typically discharged through a quench tank, the very soluble chlorides are generally washed out, especially if the quench tank is operated as a kind of washer with a slight water surplus [Reimann 1994]. In such cases, Cl concentrations in bottom ashes range from 1 - 5 g/kg. Sulphates are far less soluble due to the high Ca inventory in the ashes and hence there is only a limited wash-out to be expected in the quench tank. Ranges of sulphate concentrations in bottom ashes are reported to 3 - 50 g/kg [Belevi 2000].

A key parameter for the disposal and utilisation of bottom ashes is the TOC (total organic carbon) which characterises the quality of the burnout. In a number of EU countries, a TOC limit of 1 wt% is set for utilisation in road construction [LAGA 1994].

In modern well operated EfW plants, the TOC in bottom ashes is typically well below this number [Reimann 1994, Pfrang-Stotz 1999, Bergfeldt 2000, Vehlow 2002].

Raw bottom ashes from incineration of mixed MSW contain significant amounts of ferrous and non ferrous metal scrap. It is common practice that at least the ferrous, and increasingly also the non ferrous, metals are recovered. If it is intended to use the bottom ashes, the obligatory post-combustion treatment is much more extended. A typical flow sheet of advanced ash treatment as performed at the Hamburg, Germany, waste incinerator MVR is shown in Figure 13.

Figure 13: Bottom ash pre-treatment at the Hamburg waste incineration plant MVR (adopted from [Zwahr 2006])



After discharge from the furnace, the ashes are stored for a few days for de-watering before they undergo further treatment which consists of sieving to remove bulky fractions and magnetic separation of ferrous scrap and eddy-current separation of non-ferrous metals. The metal fractions, up to 10 wt% of ferrous and approximately 1 wt% of non-ferrous scrap, are sold to recycling companies.

The ashes are then stored for aging or maturing for typically three months. The aging causes a reduction of the alkalinity of the bottom ashes by the uptake of CO₂ from the air and a certain re-speciation of mineral phases. Both reactions have a stabilising effect on the ashes.

The access to a landfill or to a specific utilisation scenario depends not only on the residual carbon inventory but also on the leaching properties of the material in question. There are a

number of standardised protocols for elution testing [IAWG1997]. Some EU member countries developed their own test protocols such as the NEN in The Netherlands and the DIN tests in Germany. In future, the CEN compliance tests will be the official test procedure in the EU. Legal tests in other parts of the world are the Japanese JLT-13 test or the US EPA TCLP test which is also used in other parts of the world. A comparison of various standards for disposal, as well as for utilisation, points out that the requirements for leaching stability are more or less of equal stringency around the world.

Filter ashes

Filter ashes are deposited at temperatures at or slightly below 200°C. Heavy metal compounds which are volatilised inside the combustion chamber are to some extent condensed on the surfaces of the chamber and the concentration of elements such as Cl, Zn, As, Cd or Pb can significantly exceed those found in the grate ashes. Furthermore, the inventory of low volatile halogenated organic micro-pollutants such as PCDD/F or PCB is also increased compared to that in bottom ashes since these compounds are synthesised inside the boiler. Due to their elevated pollutants inventory boiler and filter ashes have to be characterised as hazardous waste. They are typically disposed of on special - and expensive - disposal sites, including underground. In Germany they are sometimes used in old salt mines for the backfilling of caverns.

The high cost of sustainable final disposal of filter ashes is one reason for numerous attempts to detoxify these materials in order to get access to less expensive disposal routes or even to utilisation scenarios. A broad spectrum of different processes has been proposed and tested at different scales [IAWG 1997]:

- solidification and stabilisation;
- melting and vitrification;
- combined processes like the 3R Process.

For the time being, vitrification is only applied in Japan, often together with fusion of bottom ashes. The molten products have excellent elution stability. Care has to be taken to avoid air pollution by evaporation of metal compounds. The energy consumption of all these processes, however, is very high. That is why none of them - although developed and tested during the 1980s - have made it to the market in Europe. The favoured option in Europe is disposal in dedicated sites.

APC residues

The residues from wet gas cleaning without water discharge and those from dry or semi-dry APC systems carry high levels of soluble salts, especially of alkali and alkali-earth chlorides or sulphates. Due to their high solubility, a safe disposal route can only be guaranteed on special disposal sites. Attempts have been made to utilise parts of the ingredients of these residues in order to minimize the disposal problem. One challenge is the closing of the chlorine cycle. Different processes to recover NaCl [Karger 1990], HCl [Menke 1999], Cl₂ [Volkman 1991], or gypsum have been tested. All such processes can only be successful if they end up with high quality products and if there is a long-term market for the products. Currently, in Germany only a few EfW plants produce HCl and NaCl.

A different - and finally very cheap - way of disposal of filter ashes (and APC residues) is practiced in Germany where authorities enforce the backfilling of cavities in old mines. Salt caverns are already being filled by semi-dry flue gas cleaning residues from EfW in big bags. This strategy - which is even accepted as 'utilisation' - may be justified on the basis that the chemical and physical properties of the original salt and the disposed residues are similar. However, as for similar activities in old coal mines, this argument can hardly be justified.

Thermal treatment 1: grate incineration

Technology	Incineration in grate furnaces
General concept	Combustion of untreated waste in air or oxygen enriched atmosphere on a grate Capable of burning waste with a LHV (lower heating value) of 6 - 12 MJ/kg, for higher LHV the grate or part of it is water cooled
Status of commercialisation	Oldest (since 1874) and prevailing EfW technology world wide Commercially proven, used in >500 plants Many plants have been in operation for 15 - 30 years
Combustion temperature	>850°C (>1,100°C for hazardous or high-chlorine wastes)
Size (per line)	3 - 40 t/h
Size (per installation)	Very broad; the biggest installations treat about 1.2 - 1.4 million t/a
Energy recovery	Primary or boiler efficiency: 75 - >85% Power efficiency: up to 30%, in combination with power plants higher (40%+) Heat only and CHP can reach >70%

Types of grates

A grate furnace is capable of burning untreated waste. In a grate furnace, the waste is fed in via a feeding chute and then pushed into the combustion chamber by a hydraulic ram or a travelling grate. There are a number of different grate designs in operation but their prime function is the controlled transport of the waste through the combustion chamber. The design has to guarantee efficient mixing of the fuel bed and permanent coverage of the metal parts to protect them against over-heating. In all grates the primary air is injected from below, through the grate.

Out of the three general grate elements (rolls, bars and belts or plates), the latter are today only used as feeding grates. The other types are briefly described below.

- **Roller grates** (see left part in Figures 14 and 15) use slowly turning perforated rollers to transport the waste through the combustion chamber. An advantage of such grates is that only about 30% of the total grate surface is exposed to the hot combustion chamber, whereas the other part is cooled by the primary air; hence roller grates cope well with high calorific waste. They have also been preferred for high throughputs. The whole design and especially the wear of the sealing of the roller nips make this grate type more complex and expensive than some other types.

Figure 14: Four types of common grates: roller (left), forward-acting reciprocating (centre), horizontal (right top), reverse-acting grate (right bottom)

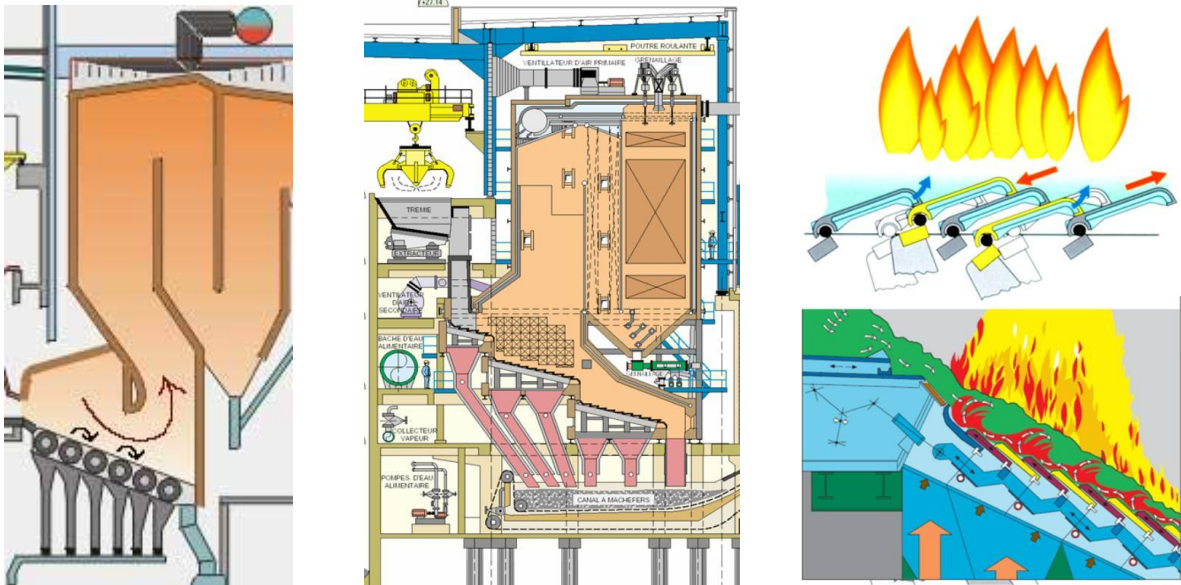


Figure 15: Combustion chamber with two lines of a horizontal grate (left) and five lines of a reverse-acting (right; adopted from [Martin 2009])



- **Reciprocating grates** are grates that use bars to transport waste. The most common designs are rows of bars, with one fixed and the next one partly stacked below the first one, moving. If the moving bars push the waste towards the end of the grate the type is called forward-acting grate or stoker. These grates are moderately inclined (see central picture in Figure 14). The figure indicates that the grate can be stepped for improved mixing.

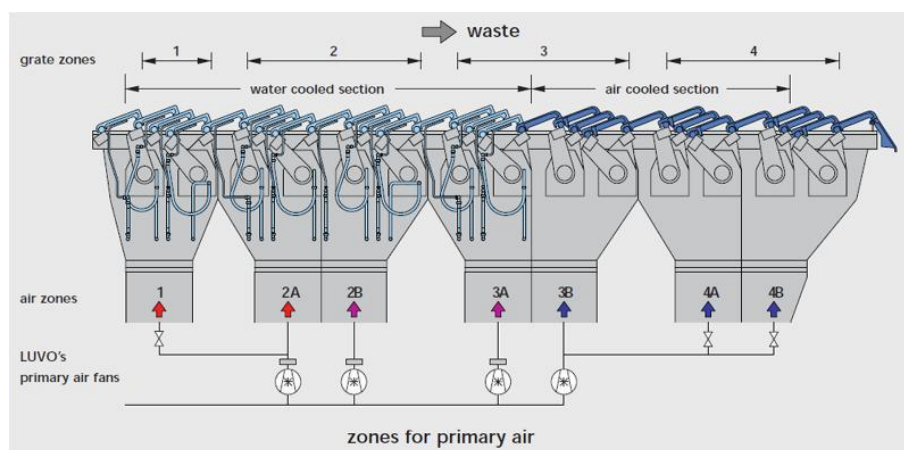
Forward-acting grates can also be built horizontally (see top right of Figure 14 and left picture in Figure 15). The figure shows the movement of the bars.

The bottom right drawing of Figure 14 and the right photo in Figure 15 show the reverse-acting or Martin grate. In this case the bars push the waste against the transport direction. This design requires a steeper angle and accomplishes a good vertical mixing of the waste.

For high throughputs, the combustion chamber can be equipped with two or more lines of bars as shown in Figure 15 for a horizontal and a reverse-acting grate.

To extend the combustion capability to LHVs exceeding 12 MJ/kg, forward-acting grates are often partly equipped with water cooled bars. The design shown in Figure 16 has been used in the new lines of the AEB Amsterdam waste incinerator [AEB 2010].

Figure 16: Water cooled horizontal grate in the AEB Amsterdam incinerator



Combustion chamber

The combustion chamber can be configured as counter-, middle-, or parallel-flow system, depending on the location of the flue gas exit. The different designs are seen in the schemes of full scale facilities shown in Figures 20 to 23.

Mass flow

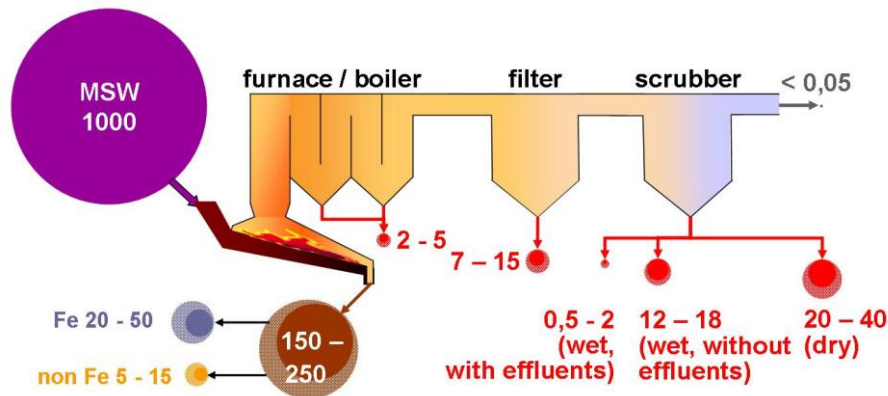
Figure 17 shows average ranges for the mass flow as found in modern waste incinerators [IAWG 1997]. The air consumption is approx. 4,500 m³/t of waste.

In Western industrialised countries, between 15 and 25 wt% of the waste feed leaves the plant as bottom ashes. In Japan, this share is in the order of 10 - 15 wt%. Most published data include the grate siftings which are only recently, and only in some countries, kept separate from the bottom ash. The mass flow of siftings depends on the type of grate and its time of operation. The siftings may increase the amount of unburnt matter in the bottom ash.

In view of utilisation, however, the inventory of metallic aluminium, which tends to drip through the grate voids, is of much higher concern.

The bottom ash contains significant amounts of ferrous and non-ferrous metal scrap which is now routinely recovered using magnetic and eddy current separation.

Figure 17: Schematic of typical mass flows in a MSW grate incinerator



The amount of boiler ash (the ash deposited in the boiler) depends on the type of boiler and on the dust load of the flue gas leaving the combustion chamber. Mean figures in modern plants are 2 - 5 kg per t of waste. Boiler ashes should not be combined with the grate ash, but be treated together with the filter ash; this requirement has been enforced by legislative regulations in some countries.

The fine particulate fly ashes are preferentially removed from the flue gas by ESP or fabric filters. The amount produced is dependent on the raw gas fly ash concentration - usually in the range 1.5 - 5 g/m³. Dust loads in modern waste incinerators which use a so-called 'gentle' combustion in order to limit the PCDD/F formation inside the boiler [Vogg 1991] are found at the lower end of that range.

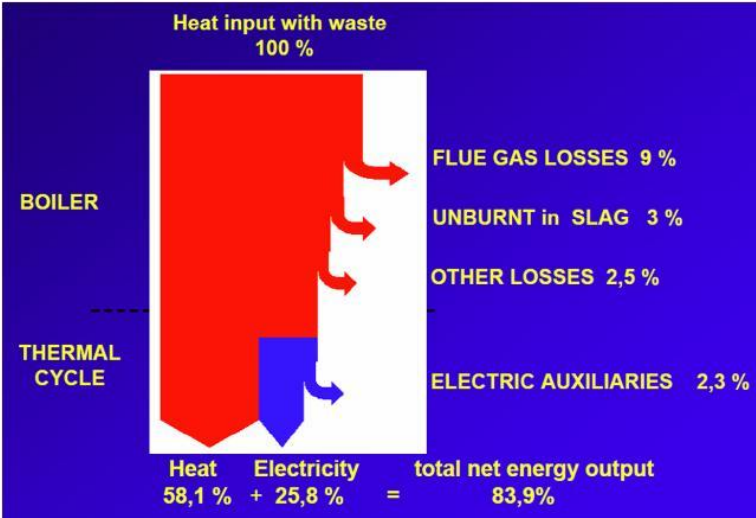
The mass flow of APC residues shows actually the highest variation of all residues. As described above, a wet scrubber is operated close to stoichiometry. If the discharge of scrubber effluents - after cleaning and neutralisation - into a sewer is permitted, the residue, a neutralisation sludge comprising mainly metal hydroxides, is only in the order of approx. 0.5 - 2 kg. In case of wet scrubbing with effluent evaporation another 12 - 18 kg of dried soluble salts have to be added.

In semi-dry or dry systems the amount of residues is significantly increased because of unreacted additives. The 20 - 40 kg per t of waste is a typical value found in modern waste incineration plants.

Energy flow

As an example of the energy flow in a modern waste incineration plant, Figure 18 shows the energy balance of the energy optimised waste incinerator in Brescia, Italy.

Figure 18: Energy balance for the Brescia, Italy, waste incineration plant



The flow scheme documents a primary or boiler efficiency of about 85%. For other plants, even slightly higher figures have been reported.

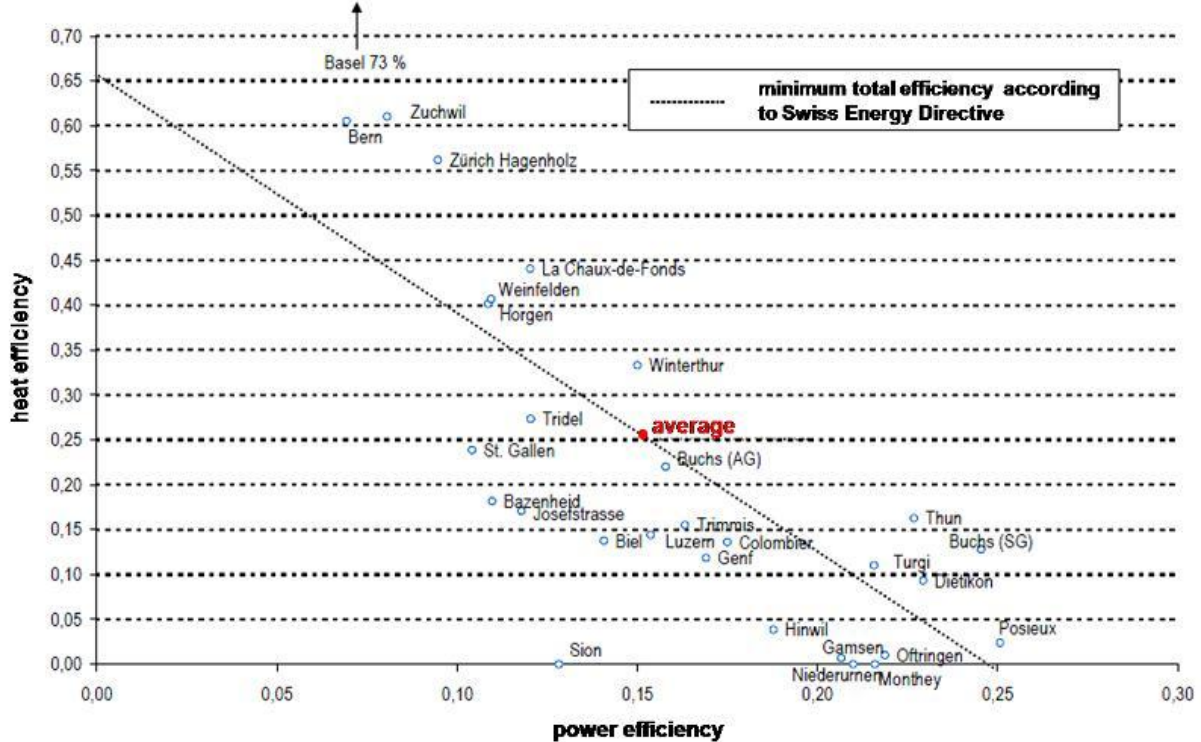
In the case of Brescia, a power efficiency of almost 26% is achieved, which allows a net power export 24.5% of the initial heat input. Most plants, however, reach only 15 - 20%.

CHP is practiced increasingly for better utilisation of the energy inventory of the waste. In Brescia, 58% of the waste input energy is used as heat. Other plants which are only designed for heat utilisation (as in Sweden), reach efficiencies in excess of 70%.

The variation in the energy efficiency of 29 existing (Swiss) waste incineration plants is shown in Figure 19 [Hügl 2008]. There are plants like Fribourg-Posieux with high power generation of 25%, but low heat utilisation of only 2.5%. Other plants like Basel utilise export heat (73%) but have a power efficiency of only 7%.

The tendency to optimise the energy recovery in Switzerland is indicated by the line which shows the minimum energy efficiency requirement of the Swiss Environmental Agency BAFU for new waste incinerators.

Figure 19: Distribution of heat and power efficiencies in all 29 Swiss waste incineration plants [Hügl 2008]

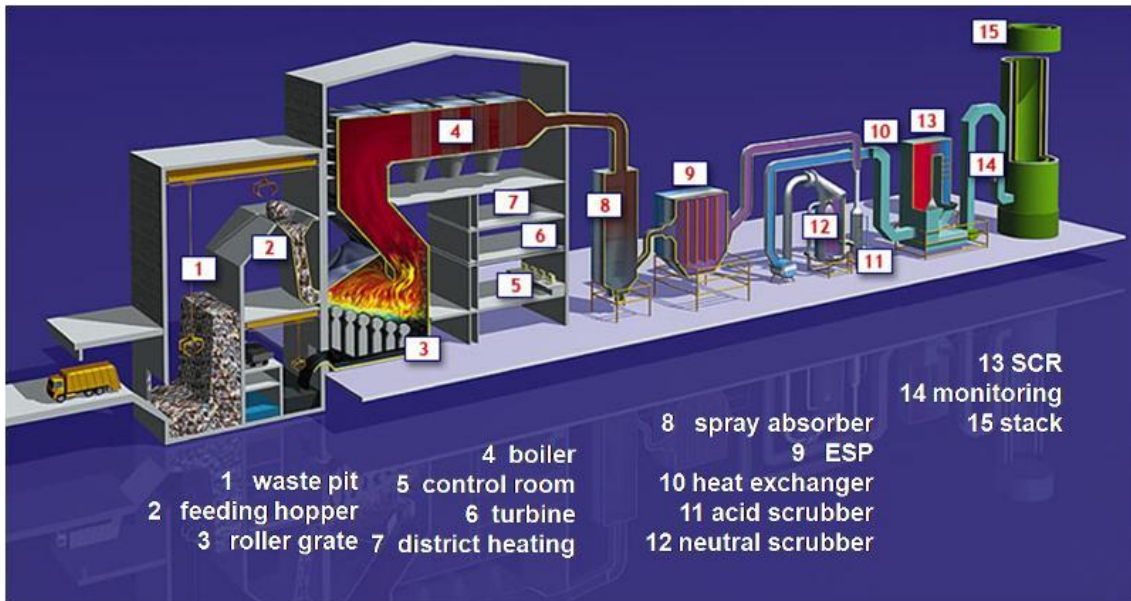


Schematics of waste incineration plants with grate furnaces

Figures 20 to 23 show schematics for four modern waste incineration plants. The flow diagrams show the design of different options that are not necessarily the most technically advanced, nor the most efficient, or the most economic. However, at the time they were developed the facilities were best adapted to the prevailing local circumstances.

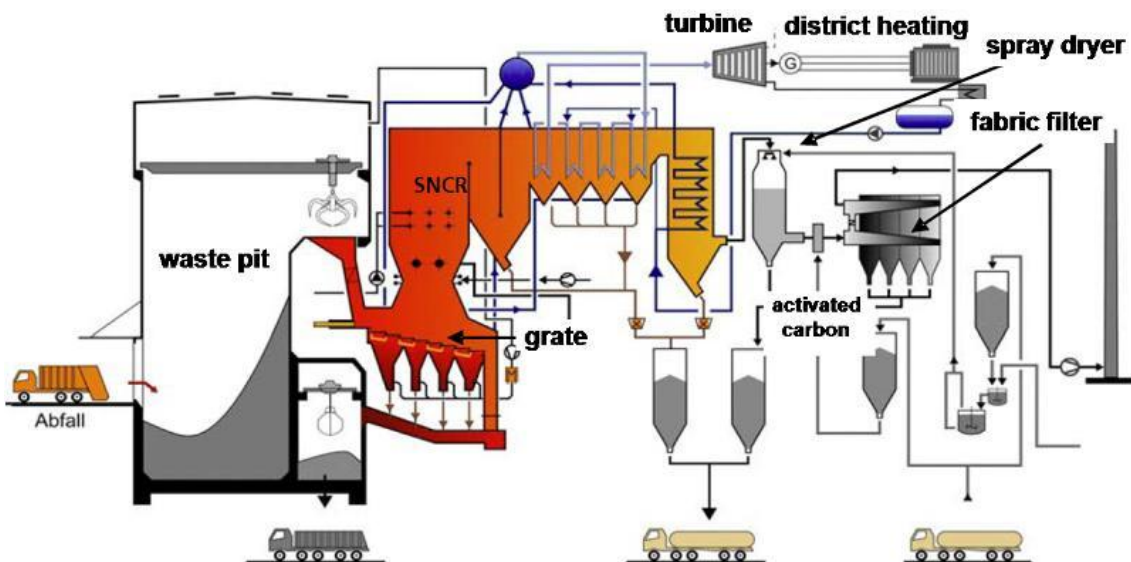
The Offenbach plant (Figure 20) was built in 1970 with (at that time) the preferred roller grate system. It was last upgraded in 1996. Its annual throughput is 250,000 t of MSW and it exports heat and power. The reported power efficiency is approximately 7% and about 31% of the energy input is used as heat. The plant has been built in a remote location and clients for heat consumption are limited. Furthermore, the boiler is of the conventional design with 400°C and 40 bar steam parameters.

Figure 20: Flow diagram of a MSW grate incinerator equipped with a roller grate, parallel-flow combustion chamber, horizontal boiler, wet scrubbing with spray dryer, SCR (Offenbach, Germany)



The plant is equipped with a wet scrubbing system with internal evaporation and a SCR for NO_x abatement.

Figure 21: Flow diagram of a MSW grate incinerator equipped with a forward-acting grate, middle-flow combustion chamber with SNCR, horizontal boiler, dry scrubbing (Leuna, Germany)

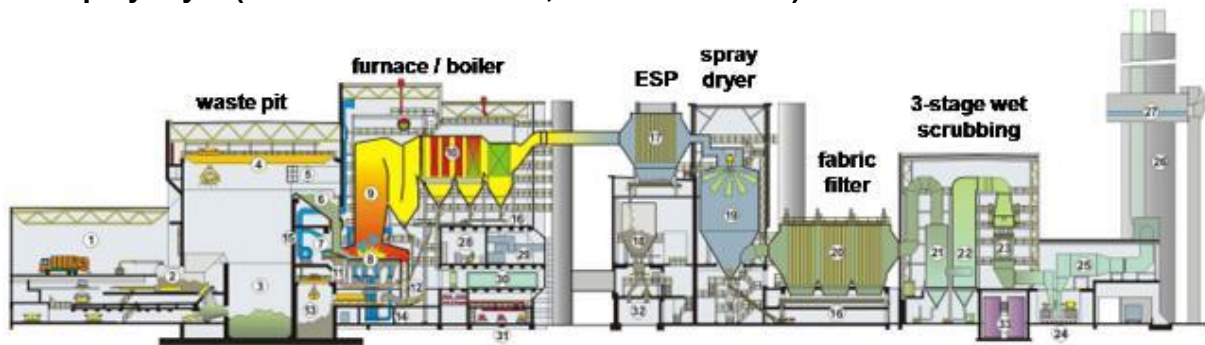


The Leuna facility (Figure 21) with a throughput of 390,000 t/a began operation in 2007. It generates power only with a net efficiency of 20%. The plant has a rather 'lean' APC system with SNCR and dry scrubbing.

The new extension of the Amsterdam waste incinerator (Figure 22) came into operation in 2007. It comprises two identical lines with a throughput of 265,000 t/a each, which makes the facility, with a total throughput of 1.4 million t, the biggest waste incinerator in the world.

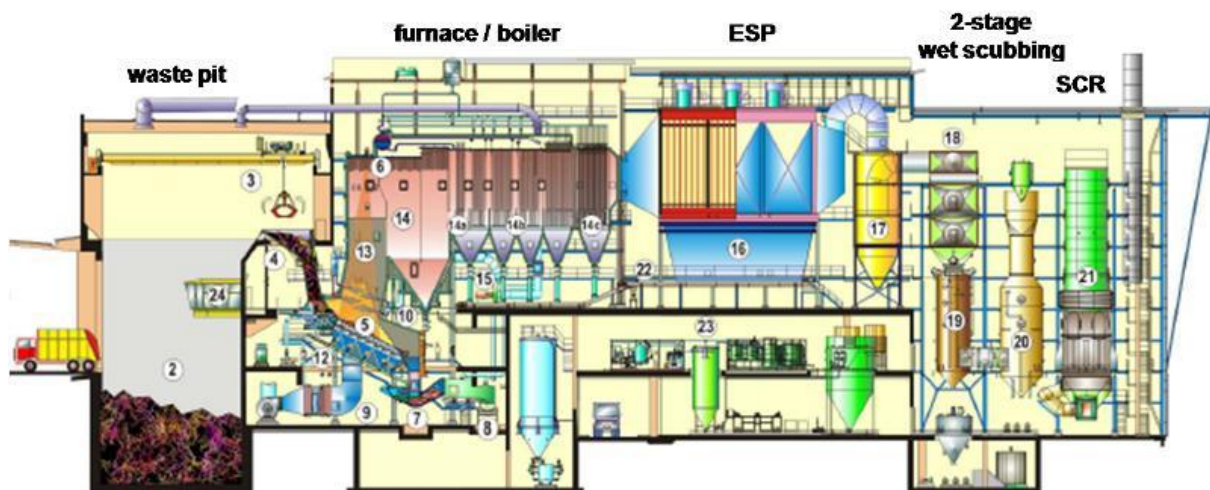
The new lines have a power efficiency of approximately 31%, which is not only due to the high steam parameters (440°C, 130 bar, but also to an additional economiser downstream of the ESP and another one in the third so-called fine scrubber. The plant produces $\text{Ca}(\text{Cl}_2)$ and gypsum from the scrubber effluents and has installed a highly-sophisticated bottom ash treatment for optimised metal recovery.

Figure 22: Flow diagram of a MSW grate incinerator equipped with a horizontal grate, middle-flow combustion chamber with SNCR, horizontal boiler, 3-stage wet scrubbing with spray dryer (Amsterdam new lines, The Netherlands)



The Swiss Fribourg-Posieux waste incinerator (Figure 23) started operation in 2001. It is a small plant with one line only and a design capacity of 88,000 t/a. In 2007 it treated 81,600 t and achieved an availability of 95%. The plant is optimised for power generation; the respective efficiency is 25% and the in-house demand is 5.7%.

Figure 23: Flow diagram of a MSW grate incinerator equipped with a reverse-acting grate, counter-flow combustion chamber, horizontal boiler, 2-stage wet scrubbing with liquid effluents, SCR (Fribourg-Posieux, Switzerland)



Architectural features

The architectural design of modern plants has become of increasing significance in most countries that utilise EfW technology. The principal driver for this is to achieve greater public acceptance. Figure 24 illustrates some of the design concepts that have been realised in different countries.

Figure 24: Pictures of selected waste incineration plants with special architectural features



NL - Amsterdam



NL - Rotterdam



F – Chartres



I - Brescia



D - Mainz



J – Maishima (Osaka)



J - Saitama



DK - Esbjerg

Thermal treatment 2: fluidised bed (FB) incineration

Technology	Incineration in fluidised bed furnaces
General concept	<p>Combustion of pre-treated (shredded) waste in a bed of sand (partly with dolomite), fluidised by air injected through nozzles in the floor of the furnace</p> <p>Preferentially used for SRF</p> <p>Waste particle size <200 mm</p> <p>The sand facilitates an efficient heat transfer and is separated from the extracted bed ash and recycled</p> <p>LHV of the fuel can change in wide ranges from < 5 MJ/kg - >20 MJ/kg</p> <p>Only atmospheric facilities are used in waste incineration</p>
Status of commercialisation	<p>For waste incineration practiced since approx. 1970</p> <p>Commercially proven, used in >50 plants for MSW incineration</p> <p>Mainly used in Japan for smaller throughputs</p>
Combustion temperature	<p>Bed temperature 800 - 850°C</p> <p>Freeboard temperature >850 - 1,100°C</p>
Size (per line)	3 - 15 t/h
Size (per installation)	<10,000 - 660,000 t/a
Energy recovery	<p>Primary or boiler efficiency: 80 - >85%</p> <p>Power efficiency: up to 25%</p> <p>Heat only and CHP can reach >70%</p>

Types of FB furnaces

FB furnaces consist of a rectangular or cylindrical combustion chamber where finely grained fuels are burned in a fluidised sand bed, sometimes with the addition of dolomite for the capture of acid gases. FB furnaces were initially developed for the combustion of sewage sludge and are today deployed mainly in Japan for the use of municipal waste. Currently, they are becoming more popular for the combustion of SRF and biomass.

The share of (waste) fuel in the sand bed is typically of the order of 2 - 10 % only, depending on the calorific value of the fuel.

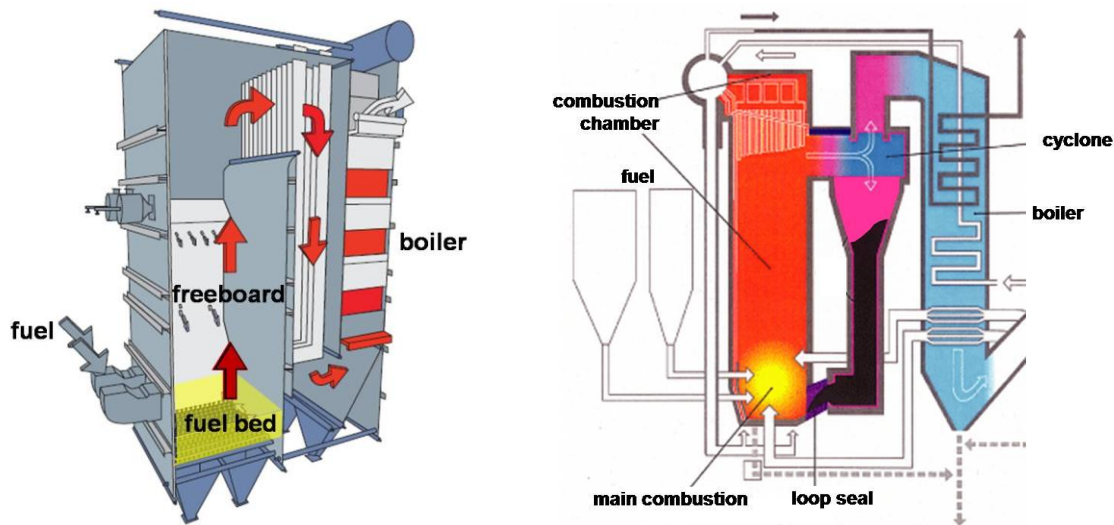
All FB furnaces have the advantage to establish a uniform distribution of the waste in the fluidised fuel bed, which enables a homogeneous and stable combustion. Another advantage is the wide range of heating value of the fuel that can be burnt in this type of furnace. The energy density in the fuel bed can be varied by controlling the share of fuel in the bed.

These advantages, however, have to be paid for by the need for pre-treatment of the fuel, as, for establishing fluidisation, the particle size of the fuel has to be limited. Another limitation is the fuel bed temperature, which is typically kept $< 850^{\circ}\text{C}$ to avoid melting of ash components and the collapse of the fluidised bed.

Three types, stationary, circulating, and revolving or internally circulating fluidised beds have been used for waste incineration.

- **Stationary** FB furnaces are the simplest designs (see Figure 25). The fluidisation forms a fuel bed which fills only a small fraction of the height of the furnace. Depending on the expansion and fluidisation this type is often also called bubbling fluidised bed.

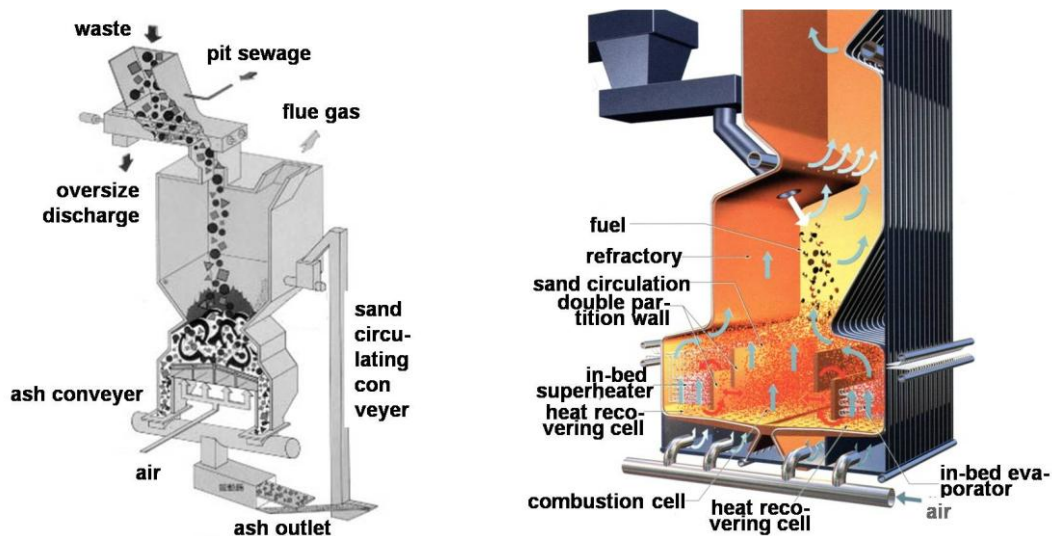
Figure 25: Stationary (left) and circulating (right) fluidised bed furnaces



- **Circulating** FB furnaces (see Figure 25) operate with higher suspension, which causes an entrainment of part of the bed material out of the combustion chamber. This material is precipitated in a cyclone and fed back into the furnace.

For better fuel bed temperature control and more efficient energy extraction, part of the boiler is integrated in the combustion chamber walls. In some furnace designs the superheater is placed in the area where the sand is fed back into the furnace. In this area, almost no chlorides are present in the material, which reduces the corrosion risk. Experience shows that erosion on the boiler tube walls is not a problem.

Figure 26: Two schemes of revolving or internally circulating fluidised bed furnaces



- **Revolving** - also called internally **circulating** - FB furnaces (see Figure 26) have a design that establishes internal horizontal eddies and increases the residence time of the fuel in the lower part of the furnace. Such FBs cope with more coarse fuels. In most cases the feeding system is a twin-screw mechanism, which acts as a kind of shredder. The resulting particle size can exceed 20 cm - big hard lumps are discharged (see left furnace in Figure 26).

The larger particles burn on the (in most furnaces) inclined floor until they can be discharged at outer ash discharge ports (left design in Figure 26) or in the centre opening (see right design in Figure 26).

In new plants, evaporator and superheaters are often installed in cells in the outer parts of the fuel bed for the same reason as in the case of circulating FBs (see left furnace in Figure 26).

More than 140 plants using the revolving FB furnace are in operation.

Mass and energy flows

Mass and energy flows are not fundamentally different from those for grate based incinerators. A typical mass balance cannot be established since the total amount of residues and especially the amount of bed ash, depends strongly on the degree of pre-treatment of the waste. A complete mass balance of a selected EfW process must of course include all process stages, which means the mass flow in the sorting and pre-treatment also has to be taken into account.

The total amount of solid residues is the same in all combustion processes, provided the burnout is of equal quality. The distribution, however, depends on the process applied and that means, as a common rule, that the amount of fly ash is typically much higher than in grate systems. The few published reports underline this assumption.

Due to the small particle size and the long residence time in the sand bed, the burnout of bed as well as of fly ash and the gas phase is always excellent.

The gas cleaning processes are common for all combustion processes and if the same fuel is burnt, the APC residues are also identical, again independent of the combustion process. However, since waste for FB plants is pre-treated, it should be assumed that the amount of pollutants in the fuel is lower than in mixed MSW and that hence the amount of APC residues is lower, too.

The energy balance is also in principle not different from that of a grate incineration plant. Considering the use of pre-treated and typically higher calorific waste, the energy input per ton of fuel is higher and so are the generated energies. The percentile energy flow, however, is fully in line with the overview energy balance shown in Figure 6.

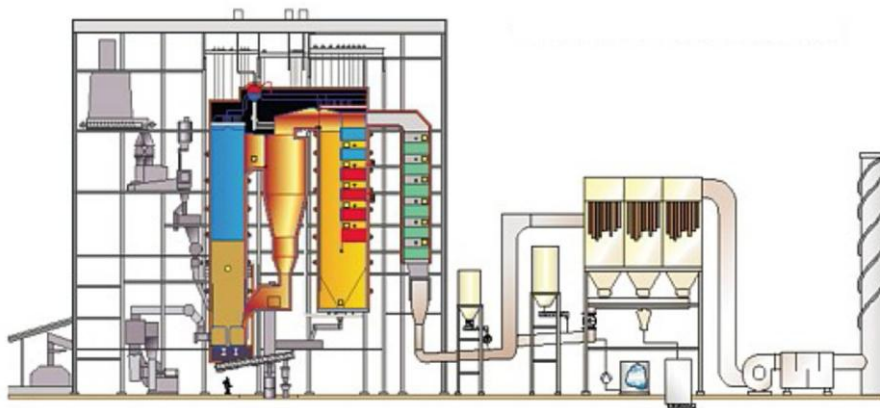
Schematics of waste incineration plants with FB furnaces

The layout of FB incineration plants is in principle identical with that of grate based plants, except for the furnace. That means the furnace is followed by a heat recovery boiler. In most cases, vertical boilers are installed. The cooled flue gas enters one of the gas cleaning systems as described above. The selection of FB systems depends on local conditions and sometimes political preference and not on the combustion technology.

FB incinerators are mainly found in Japan, but also for combustion of SRF and co-combustion in Sweden and the Iberia peninsula.

The Norrköping facility, equipped with a circulating FB furnace, started operation in 2003. The plant has a thermal capacity of 75 MW and is equipped with SNCR and dry gas cleaning. The flow diagram of the plant is shown in Figure 27 [Wilén 2004].

Figure 27: Flow diagram of the Norrköping FB waste incineration plant



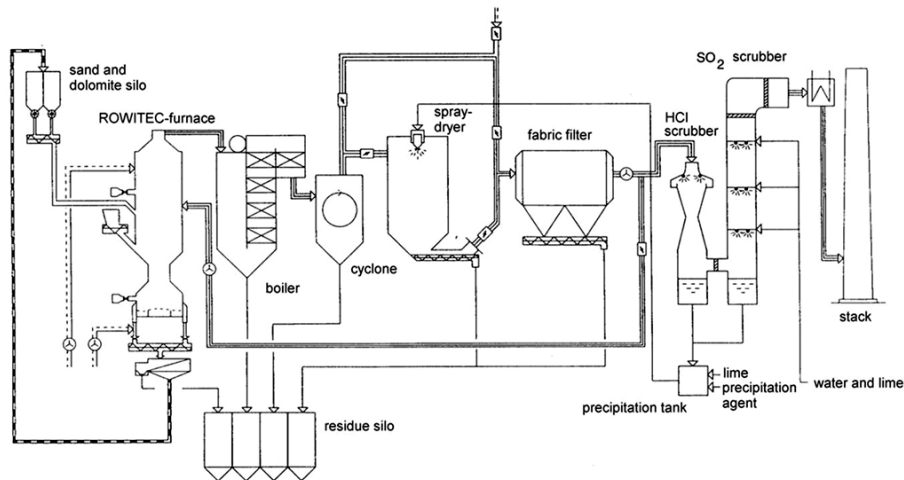
An almost identical configuration is found in Coruna, Spain, in the SOGAMA FB incinerator. This plant started operation in 2000. It is part of a complex with an SRF production facility. The incinerator has a capacity of 1,200 t/d, which adds up to approximately 400,000 t/a.

The revolving FB technology has been used in the waste management centre Tirmadrid in Madrid-Valdemingomez with a recycling, SRF, composting, and SRF combustion plant. The latter one has three identical lines with an SRF throughput of 80,000 t/a each.

The flow diagram is very similar to that of the ROWITEC plant, which was built during the 1990s in Berlin-Ruhleben, Germany, but had to be dismantled after a short operation time due to poor waste quality.

The scheme shown in Figure 28 of this Berlin plant visualises a cyclone for precipitation of primary fly ash and a spray dryer for evaporation of the effluents from the two-stage wet scrubbing system downstream of the fabric filter. In the Madrid plant, the wet scrubbers are missing and the gas cleaning is performed by injecting slaked lime and activated charcoal into the spray dryer.

Figure 28: Flow diagram of the Berlin-Ruhleben FB waste incineration plant (out of operation)



External Appearance

The three plants shown below are of:

- The Madrid-Valdemingomez plant at the end of the construction phase. The three revolving FB furnaces are seen in the foreground.
- The second aerial view shows the circulating FB SRF plant in Coruna (in the background) with SRF production plant and composting facility.
- The third picture shows the SRF combustion plant in Omuta, Japan, a revolving FB plant with three lines, 105 t/d throughput each.

Figure 29: Aerial views of FB combustion plants



ES – Madrid-Valdemingomez



ES - Coruna



J - Omuta

Thermal treatment 3: gasification

Technology	Gasification in various types of reactors
General concept	<p>Mainly multi-stage processes with gasification of waste in shaft or fluidised bed furnaces, in gasification chambers, in entrained flow systems or on grates</p> <p>The synthesis gas can be used for chemical synthesis, fed into gas engines, directly burnt, or co-combusted in power plants</p> <p>All processes end up with molten solid residues</p>
Status of commercialisation	In Japan, 95 plants with 195 lines and a total throughput of approx. 17,500 t/d
Temperature	<p>Gasification: 300 - 1,400°C</p> <p>Post combustion chamber: up to 1,350°C</p>
Size (per line)	< 1 - 11 t/h
Size (per installation)	<10,000 - 150,000 t/a
Energy recovery	<p>Primary energy efficiency typically > 80%</p> <p>Power efficiency: Ebara claims 22 - 33% depending on waste type and plant size, however, this excludes in-house demand for operation and oxygen production</p>

Type of gasification reactors and process schemes

There are a number of different reactor types that are in operation in waste or SRF gasification plants:

- shaft furnaces / fixed beds;
- moving beds / grates;
- fluidised beds with HT combustion of the synthesis gas or its co-combustion in a power plant;
- entrained flow systems;
- combined degassing in a channel followed by gasification in a chamber.

For the first category, Figure 30 shows the scheme of a Nippon Steel shaft furnace. These furnaces have been developed from steel furnaces and are almost always operated in co-treatment together with coal. The share of coal varies between 5 and 10%. The gasification temperature is in the order of 1,000°C, the energy for the process is supplied by partial combustion of coke and residual waste remaining in the lower part of the shaft furnace where the temperature may reach 1,800°C.

A flow scheme of a Nippon Steel shaft furnace gasification plant is shown in Figure 31. The synthesis gas is directly fed into a combustion chamber which is followed by a conventional APC system, in this case, a dry scrubbing system [Nippon Steel 2010].

Figure 30: Scheme of and reactions in a Nippon Steel shaft furnace

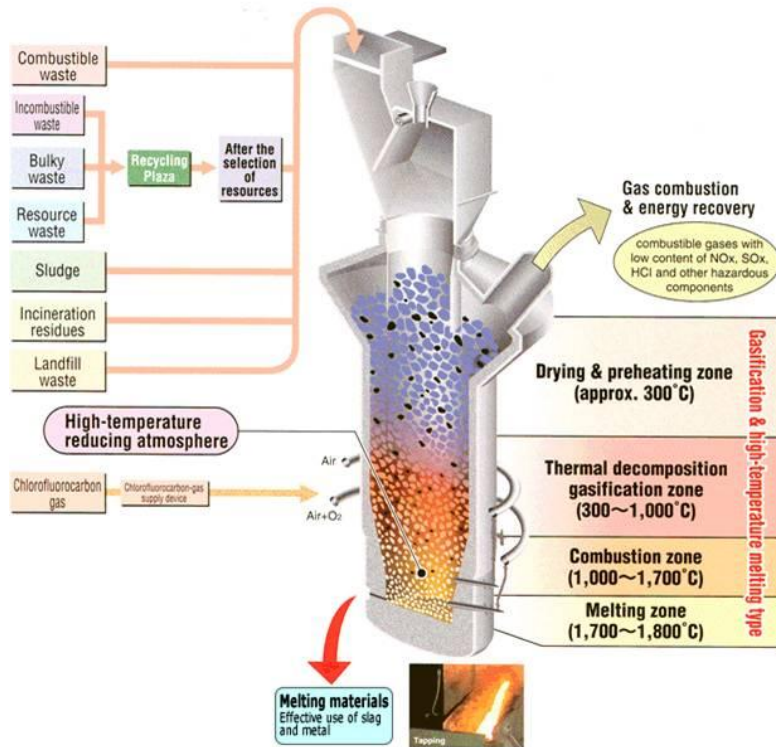
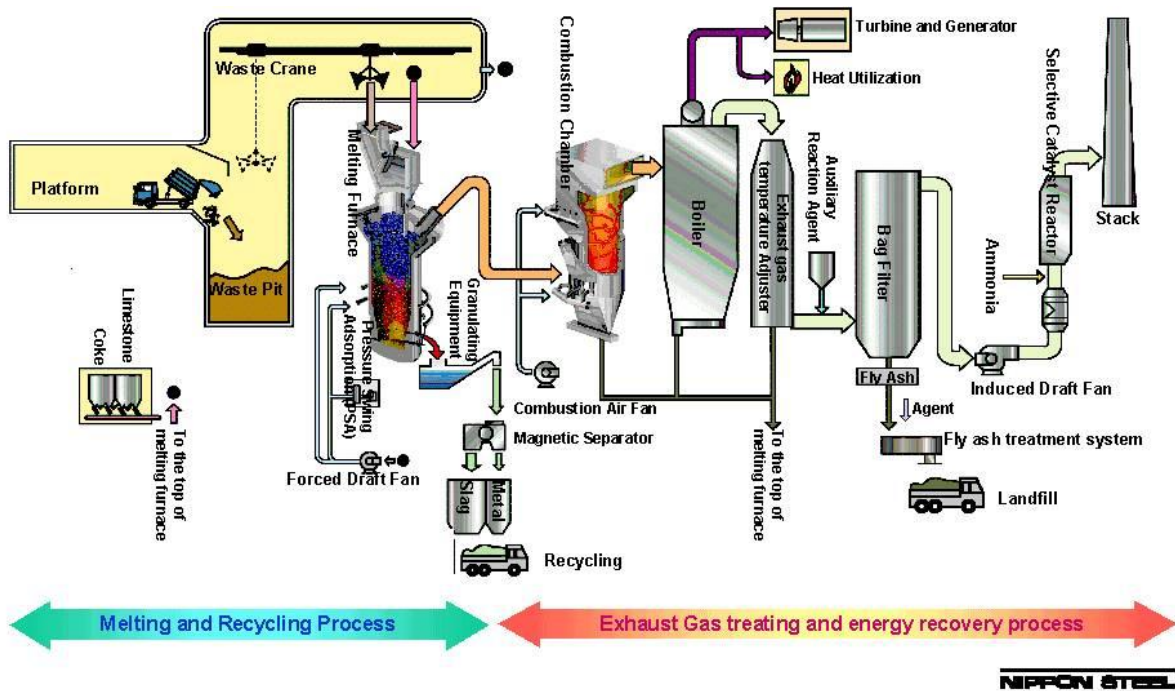


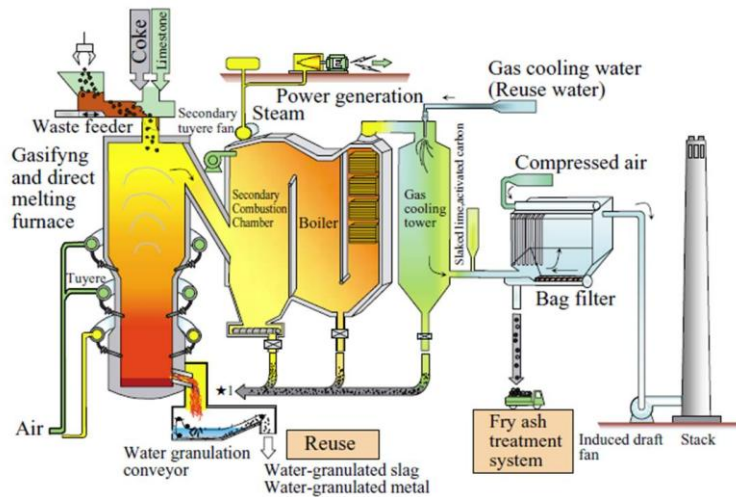
Figure 31: Flow diagram of a Nippon Steel MSW gasification and combustion plant



Nippon steel built 28 such plants with 57 lines and a capacity of 6,200 t/a in Japan.

A similar process is the JFE High-Temperature Gasifying and Direct Melting System. A flow diagram is depicted in Figure 32 [Nishino 2009]. The gasifier also treats waste with a small addition of coke; limestone is added for capture of sulphates. JFE has built ten plants with 20 lines and a total capacity of 1,500 t/d.

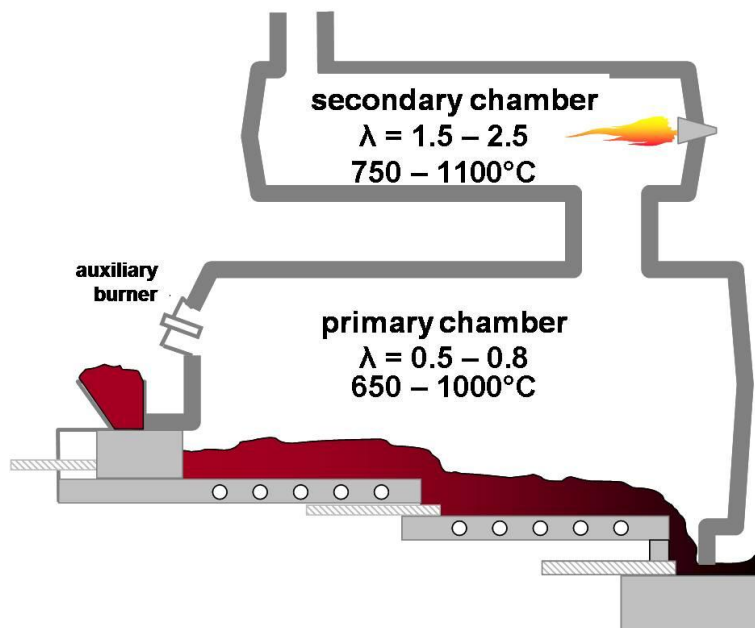
Figure 32: Flow diagram of the JFE High-Temperature Gasifying and Direct Melting System



There are four other minor companies building shaft furnace plants. The entire number of implemented facilities is 47 with 93 lines and a capacity of 8,500 t/d.

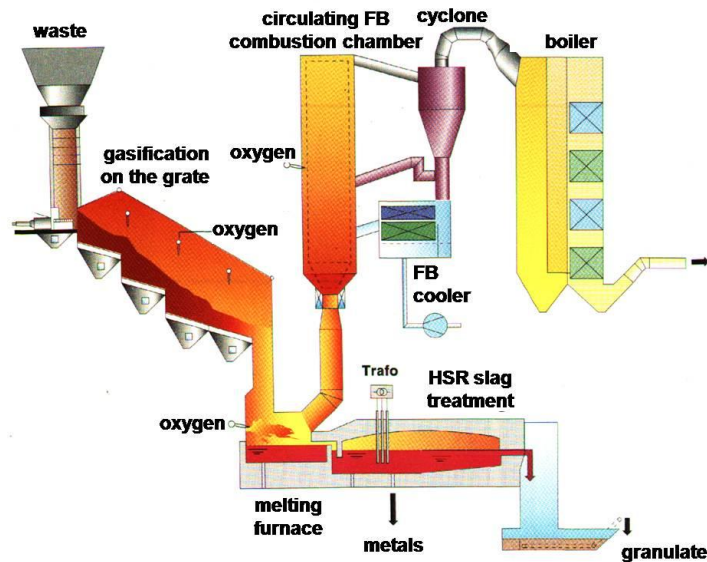
A quite different system is the Consumat Two-Stage Combustion that has had a limited market in the United States and Canada for small sizes (capacity few t/h). The scheme of the furnace in Figure 33 shows two combustion chambers on top of each other. The lower chamber is operated under sub-stoichiometric oxygen supply, which means it can in fact be called gasification. The plants were equipped with boiler and APC system.

Figure33: Furnace of a Consumat Two-Stage Combustion plant



A complex process combining gasification in a grate furnace with combustion in a FB and ash melting in a melting furnace is the RCP Process, developed in the mid 1990s by vonRoll. A first plant with a throughput of 6 t/h was built in Bremerhaven, Germany, on the premises of the existing waste incinerator. The plant was closed after a few years of operation (1997 - 2003) due to financial problems. However, the process is currently offered in Japan by Hitachi. Figure 34 shows the thermal part of a RCP plant.

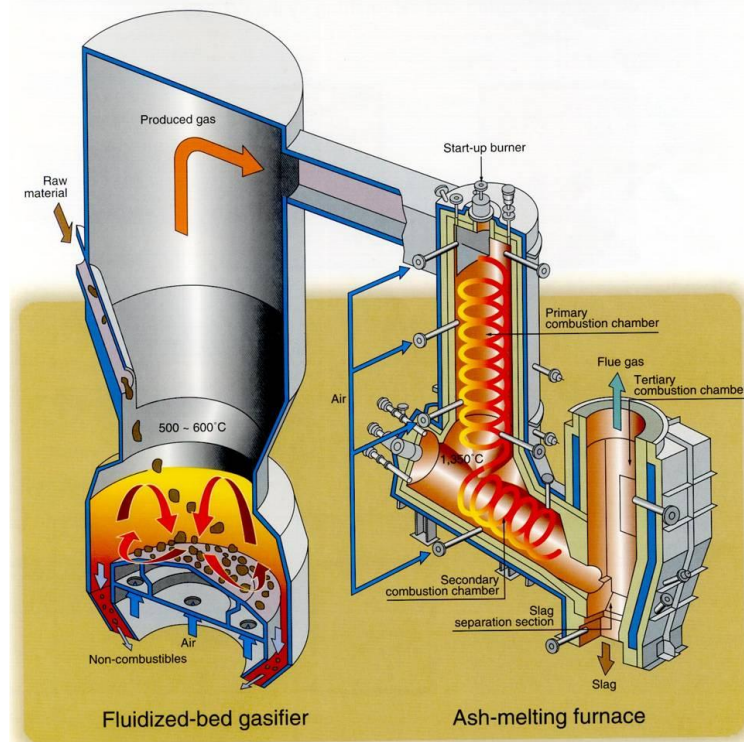
Figure34: vonRoll / Hitachi RCP Process (without APC system)



Fluidised bed gasifiers are the second successful technology in Japan. The leader in this market is the Ebara TIFG Process which combines gasification in a revolving FB with a cyclone combustion chamber. A scheme of the gasification and combustion part of such plants is shown in Figure 35.

The gasification temperature is 500 - 600°C; the combustion takes place at 1,350 - 1,450°C. The combustion chamber is followed by a boiler and a conventional APC system. The gasification residues are ashes; those from the high temperature combustion are molten slags.

Figure 35: Scheme of the revolving FB gasifier and the cyclone combustion chamber of the Ebara TIFG Process

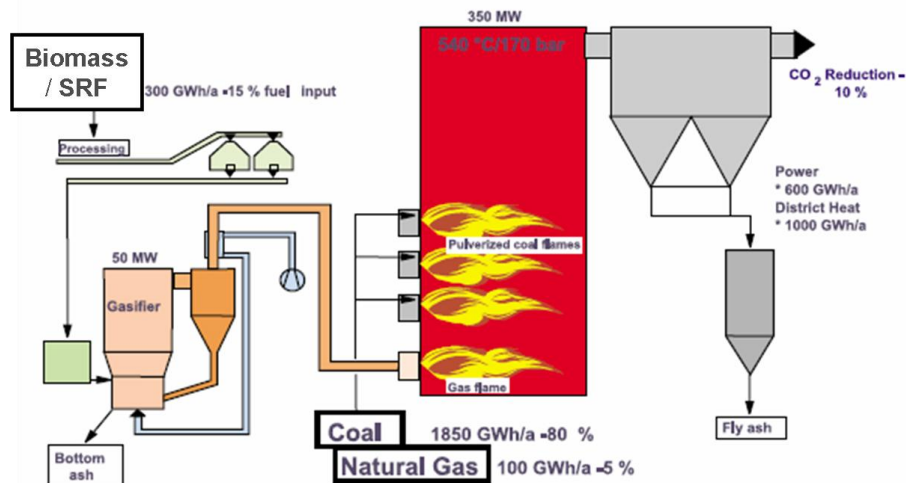


Ebara built 12 plants of this type in Japan, with 28 lines and a capacity of 3,100 t/d. The plants not only treat MSW, but also special waste fractions like automotive shredder residues (ASR) or waste plastics.

In Finland, a FB gasifier has been in operation for source-separated plastic-rich household waste in the city of Lahti [Nieminen 2005]. The plant no longer treats MSW due to the new Finnish air emission regulation. However, a new plant based on the same principle but equipped with an APC system is being proposed.

In Lahti, the synthesis gas is directly injected into the Kymijärvi coal and gas fired power plant. A scheme of the Lahti gasification / co-combustion system is shown in Figure 36.

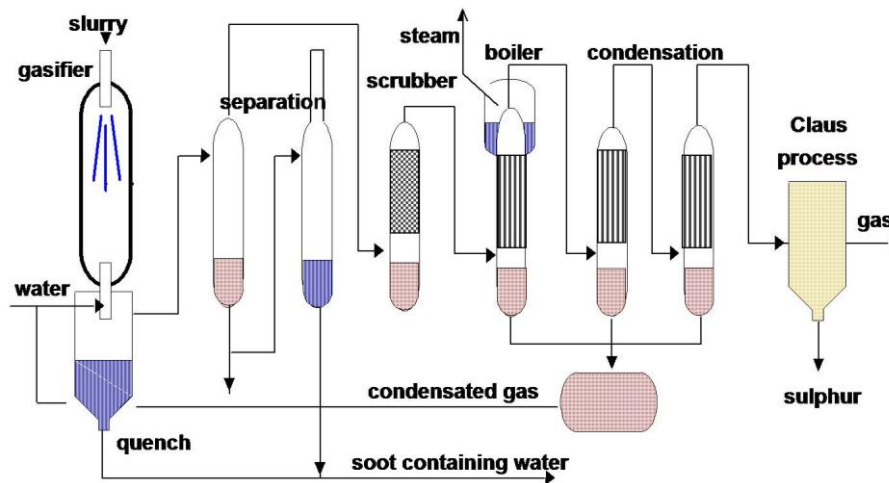
Figure36: Flow diagram of the Lahti gasification / co-combustion system



The huge Schwarze Pumpe entrained flow gasification plant, originally built for lignite, has been in operation close to Cottbus in Germany. The plant gasified lignite and SRF produced from MSW; the synthesis gas was used for methanol production. The plant also had fixed bed gasifiers which partly also fed with SRF.

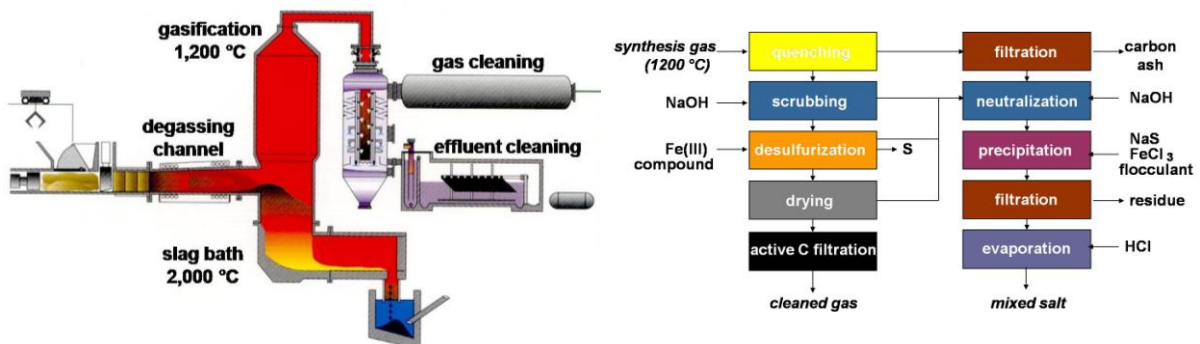
The whole plant had an annual throughput in the order of 300,000 - 350,000 t. It was shut down a couple of years ago due to financial problems. A flow diagram of the rather complex process is shown in Figure 37. The problem was the gas cleaning, which has high operational costs to meet the requirements of the methanol synthesis. A special challenge is the removal of sulphur compounds.

Figure 37: Flow diagram of the entrained flow gasifier plant at Schwarze Pumpe, Germany



Another complex process, based on degassing of the waste at elevated temperature, high temperature gasification (1,200°C), and residue melting (2,000°C) is the Thermostelect process [Stahlberg 1995]. The process aims for optimisation of energy and material recovery. The synthesis gas can either be used for methanol or other synthesis, it can drive a gas engine or it can be burnt. In case of synthesis, again, as in the case of Schwarze Pumpe, the gas cleaning results in high costs.

Figure 38: Flow diagram of the Thermostelect process (left) and scheme of the synthesis gas cleaning (right)

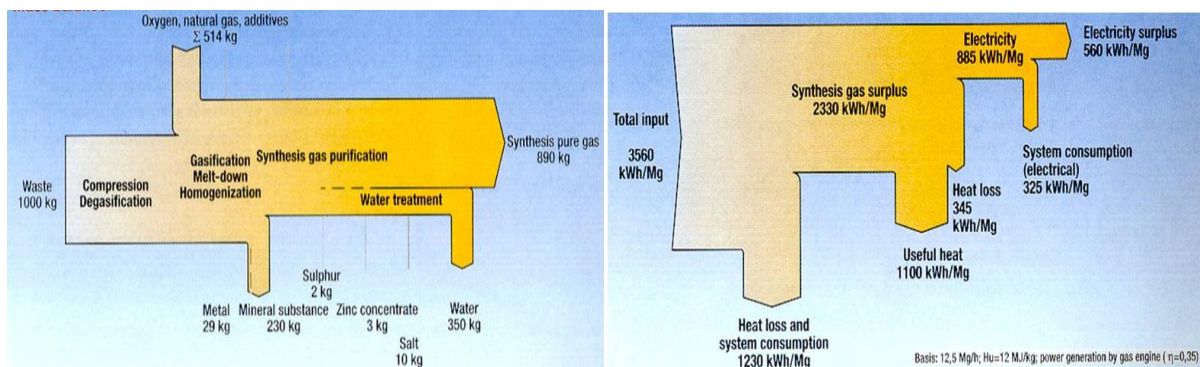


A flow diagram of the process is shown in the left part of Figure 38; the right part shows the multi-stage gas cleaning concept at the first German plant in Karlsruhe, which has, like other so-called novel processes, been shut down after a short operation time for financial reasons.

For the Karlsruhe plant, mass balances and energy balances have been published, but were, however, calculated before the plant started on the basis of results from pilot plant tests in Fondotoce, Italy. The balances are shown in Figure 39.

Since the Karlsruhe plant was equipped with a combustion chamber, the claimed 25% power efficiency was not achieved.

Figure 39: Mass (left) and energy balance (right) for the Thermosteel plant



The Japanese company Kawasaki, which is now part of JFE, took the licence from Thermosteel and built five plants with 12 lines and a total capacity of 1,725 t/d.

Architectural features

The Thermosteel plants are all built to a design by an Italian architect and have almost the same layout as can be seen in Figure 40, which shows the building of the mothballed plant in Karlsruhe and the first Japanese plant in Chiba, which is located on the premises of the Kawasaki steel works and began operation in 1999.

Figure 40: Thermosteel plant in Karlsruhe, Germany (left), and in Chiba, Japan (right)



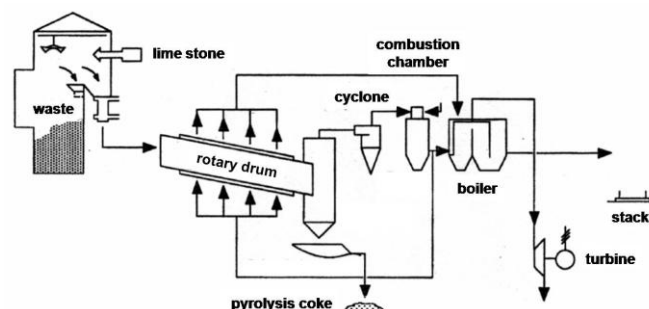
Thermal treatment 4: pyrolysis

Technology	Pyrolysis in rotary drums / HT combustion of pyrolysis gas (and coke)
General concept	<p>Pyrolysis of waste in an externally heated rotary drum, combustion of pyrolysis gas in high temperature combustion chamber</p> <p>Separation of pyrolysis coke from inert ash, in all but one plant burnt together with the pyrolysis gas</p>
Status of commercialisation	<p>First commercial plant operational in Burgau, Germany</p> <p>11 plants with 22 lines and a total throughput of 2,360 t/d in Japan</p>
Temperature	<p>Pyrolysis: 400 - 500°C</p> <p>Combustion: 1,100 - 1,350°C</p>
Size (per line)	2.5 - 8.3 t/h
Size (per installation)	28,000 Mg/a - 140,000 t/a
Energy recovery	<p>Boiler efficiency can be as high as in conventional combustion plants</p> <p>Power efficiency for one plant was reported to 15%</p>

Pyrolysis reactors and flow diagrams

Pyrolysis of waste is applied in only a few commercial scale plants. The pyrolysis takes place in heated rotary drums at temperatures of approx. 450°C. The first commercial plant in Burgau, Germany, had an externally heated drum. Japanese plants, based on a Siemens patent, use a design with internal heating tubes (see inlet photo in the left part of Figure 42). The Burgau pyrolysis plant, built in 1984 [Fichtel 1987], has a throughput of approximately 30,000 t/a and is, following a refurbishment in 2009, still in operation. Figure 41 shows the flow diagram of this plant (without APC system). The pyrolysis reactor is an externally heated rotary drum, the synthesis gas passes a cyclone and is then fed into a combustion chamber. The combustion chamber is connected to a boiler, which drives a turbine. The combustion chamber also feeds a stack. Pyrolysis coke is collected from the rotary drum.

Figure 41: Flow diagram of the Burgau pyrolysis plant



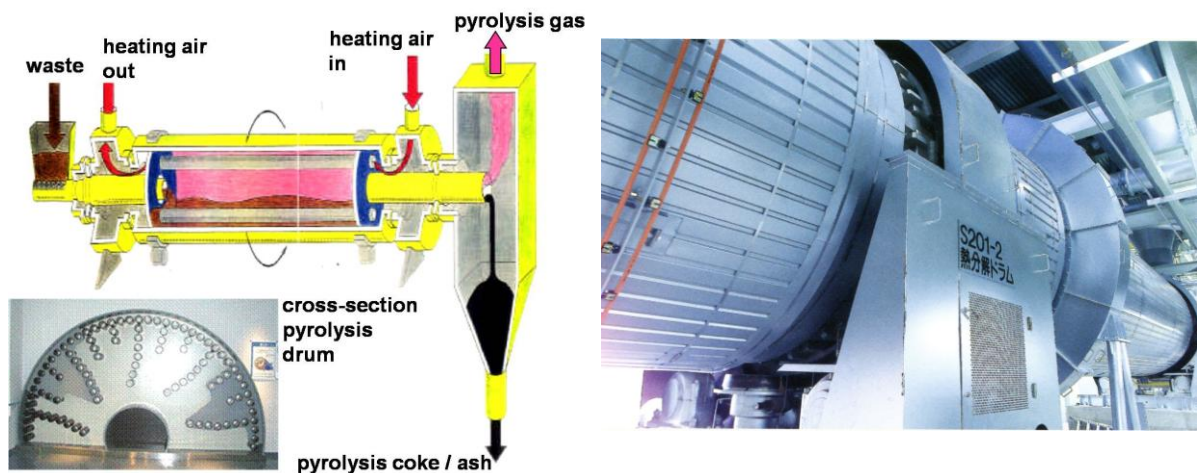
The plant is equipped with a heat recovery boiler and an APC system.

Towards the end of the 1980s, the German company Siemens started the development of a similar system, the Siemens Thermal Recycling Plant, which used a rotary drum with internal heating tubes for pyrolysis. In this process the pyrolysis gas was to be fed directly into a combustion chamber. On top of that the pyrolysis coke was separated from the mineral residue fraction and also burnt together with the gas.

Siemens built a full-scale technical plant of the process in Fürth, Germany. However, failures in the drum sealing and clogging of the gas transfer line caused the closure of the plant during its commissioning phase. Siemens withdrew from the market.

Two Japanese companies, MES and Takuma took licenses and brought the process to the Japanese market. The MES system is called R21 Process. The 3.1 m wide and 23 m long pyrolysis drum of this process is shown in the right part of Figure 42.

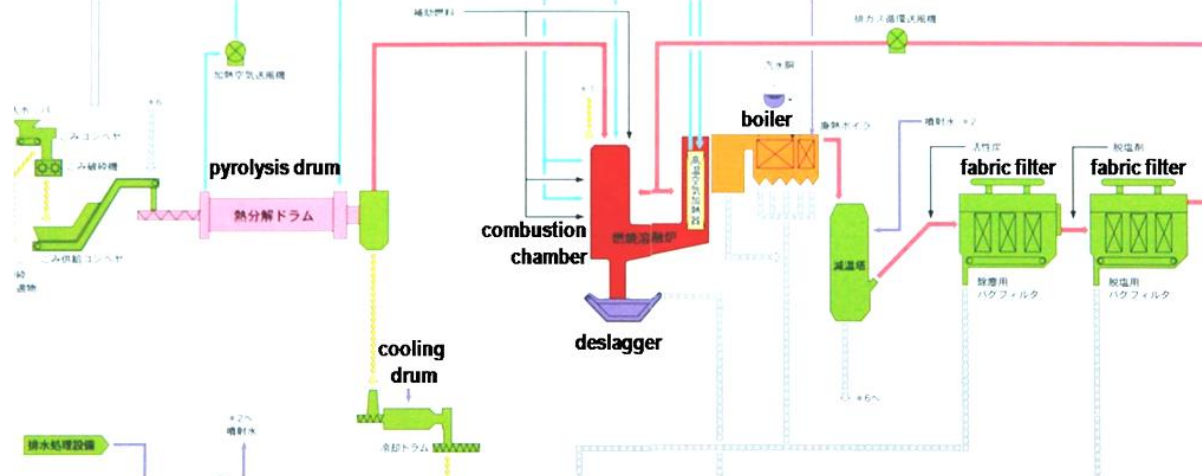
Figure 42: Scheme (left) and picture (right) of the rotary pyrolysis drum of the MES R21 Process



The pyrolysis temperature is 450°C, and the residence time 1 - 2 h. At the backend of the pyrolysis drum, the gas is extracted and fed directly into a combustion chamber where it is burnt at 1,350°C.

The solid residues pass a magnetic and eddy current separation step for metal recovery and an air classifier for separation of the pyrolysis coke from the mineral residues. The coke is burnt together with the gas; the mineral fraction is either land filled or used as aggregate. A simplified flow diagram of the MES R21 Process is illustrated in Figure 43.

Figure 43: Simplified flow diagram of the MES R21 Process



The process offered by Takuma is almost identical to the R21 Process.

MES built seven plants in Japan with 15 lines and a total capacity of 1,840 t/d; Takuma built another four plants with seven lines and a capacity of 518 t/d.

Architectural Features

Whereas MES used well-designed architecture for the R21 plants, the only picture that was found for a Takuma plant shows a pure industrial setup.

The plant in Toyahashi is the biggest MES R21 plant, with two lines, 200 t/d each. The plant became operational in 2004. The other MES plant is located in Koga city on Kyushu Island. It started operation in 2003 and has two lines with a throughput of 130 t/d each.

Figure 44: Three plants for pyrolysis with HT combustion in Japan



MES R21 plant Toyahashi



MES R21 plant Koga



Takuma pyrolysis plant

Mechanical and biological treatment (MBT) of MSW

Technology	MBT
Is the technology commercial?	Established technology in many parts of Europe and the world ¹ . It is seen as an option for treatment for residual MSW remaining after recovery of source segregated wastes. MBT can contribute to the diversion of waste from landfill and increase recycling and/or energy recovery. However, it is an intermediate treatment technology and viable end-use or disposal options may still be needed for many of outputs of MBT.
General concept	Combination of mechanical and biological plant in various configurations, designed to improve recycling, biologically stabilise waste and produce residues appropriate to end markets or stabilised for disposal in landfill.
Size	50,000 to 500,000 t/a
Energy recovery	Through combustion of combustible residues, commonly know as refuse derived fuel (RDF), if composed of a simple fraction of the residual waste or solid recovered fuel (SRF), if the material has undergone significant processing. This can be in co-combustion (e.g. in cement kilns), in co-firing (in power stations equipped to meet incineration emission limits) or in purpose built facilities. MBT with anaerobic digestion as the biological treatment also produces biogas as energy recovery.
Temperature of incineration	Depends on how the RDF/SRF produced is combusted.

What is MBT?

MBT *partially* processes MSW by mechanically removing parts of the waste and by biologically treating others, so that the residual fraction is small, stable and more suitable (than MSW) for a number of possible applications. MBT is neither a single technology nor a complete solution to waste treatment, but is a generic term describing biological and mechanical process elements that are combined in a wide variety of ways to meet a range of objectives (Juniper 2005). The main reasons for using MBT would be to reduce the amount and environmental impact of landfilling residual waste, by improved resource recovery through increased recycling, producing a residue that is combustible and can be used as a fuel, and stabilising any residuals that are landfilled.

MBT systems vary in complexity and functionality, but generally they have a sorting and materials recovery facility that is integrated with a form of biological treatment, either composting or anaerobic digestion. Some MBT processes result in residues comprised of mixtures of combustible materials (e.g. plastics, textiles, wood, dried biomass) that cannot be recycled, but have a relatively high (for waste) calorific value and are therefore suitable for combustion. Frequently, such residues are called refuse derived fuel (RDF) if prepared from the simple separation of combustibles from the feedstock or solid recovered fuel (SRF) if the

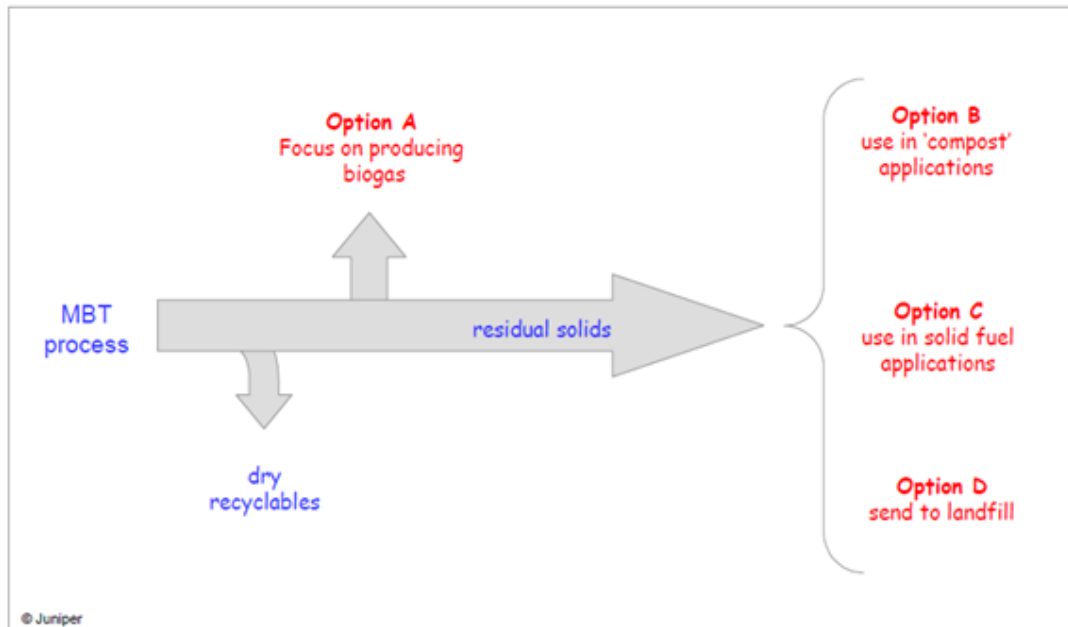
¹ There are for example plants in operation in the UK, Germany, Austria, Italy, France, Spain, Israel, Australia, USA and the Netherlands.

processing has been more extensive to derive a defined fuel product. These solid products may then be used as fuel in energy from waste plants that may involve incineration, gasification or pyrolysis.

Several generic MBT configurations may be identified, all of which may have variants capable of producing fuels for energy recovery. This section discusses these generic MBT configurations and how they may be applied for energy generation.

Figure 45 summarises the main options for MBT, focusing on the outputs.

Figure 45: The four main options for (integrated) MBT. Source: Juniper (2005)



Six generic MBT configurations are generally used:

- MBT with RDF production and composting.
- MBT with RDF production and anaerobic digestion.
- MBT with anaerobic digestion and recovery of recyclable fractions
- MBT with biodrying for SRF production.
- MBT with rapid composting and recovery of recyclable fractions
- MBT with biostabilisation.

Virtually all MBT configurations recover valuable metals at some stage of the process. Many may also recover glass and other non-metal inerts, such as stones and ceramics which may be used as aggregates. This section does not consider these further, but concentrates on processes relevant to energy generating. The key differences with regard to MBT configurations for energy are the fate of the plastics, dry biodegradable waste (paper, card, wood, textiles) and wet putrescible biodegradable wastes (kitchen and garden waste).

An MBT system will typically comprise one or more mechanical steps and one or more biological steps. These operations may occur in any sequence giving rise to descriptions as BMT for biological mechanical treatment when a biological step is first. We make no distinction between MBT, BMT or any other configuration and consider them all as MBT.

Mechanical treatment steps

The mechanical treatment part of MBT involves extensive processing of the waste, during which the waste particle size may be reduced, and/or waste separated into various fractions, which may be based on particle size by screens or on specific characteristics of the waste components, e.g. ferrous metal removed by magnets. Its main goals are to sort and treat the waste by (a) removing recyclables, (b) removing materials unsuitable for biological treatment, (c) homogenising the physical and chemical properties of the remaining fraction.

There are a number of options available for mechanical treatment, but it typically includes manual removal of materials (bulky items, white goods, cardboard), bag breakers, manual and automatic removal of recyclable materials (paper, plastics, glass, aluminium, tin cans), screening, shredding, magnetic separation and mixing using conveyors, magnets, eddy current separators, drums, shredders, air knives, hammer mills, flays and other size reducing equipment, screening for different sized components and other tailor made systems. A report available from the UK's Environment Department, Defra (2005), describes each of these processes in more detail. The remaining fraction is mainly made of organic matter which can be biologically treated.

Biological treatment

In different MBT systems, the biological stage may be short or long, be aerobic or aerobic or both, be on a defined fraction or the whole waste. Composting may be defined as the aerobic biological decomposition (i.e. degradation in the presence of oxygen) of biodegradable organic matter under controlled conditions. Composting in MBT systems typically takes place in in-vessel systems, although final maturation of partially stabilised waste may be carried out in open windrows. Particle size, moisture, temperature and oxygen are determining factors for composting. The composting period may be short (1 - 2 weeks), where it is not necessary for the waste to be fully biostabilised or up to 12 weeks or more if a fully stabilised material is required. Anaerobic digestion in MBT systems typically biologically treat only the putrescible fraction and this is over a short period (15 - 20 days), which maximises the gas production rate from the readily biodegradable fraction of the waste. The digestate is not fully stabilised and may, in some cases, be further composted to produce a stabilised material.

What are the specific disadvantages and advantages of MBT with RDF/SRF technology?

Advantages	Disadvantages
Diversion from landfill	Need for a market for RDF/SRF
Increase in recycling	Chemical properties of RDF/SRF (Cl, heavy metals contents) pose technical challenges to operation and APC during incineration
RDF/SRF can be burnt in industrial boilers, providing they meet waste combustion emission limits	Combustion plant operators may need to invest in additional processing equipment to handle RDF/SRF. There may be considerable challenge to use in some combustion plant (e.g. coal power plant).
Production of an energy carrier which can be used when and where needed	Variable quality of RDF/SRF
Once MBT plant is operating, it is an available and plentiful fuel source of RDF/SRF	Market: RDF/SRF is in competition with cheaper fuels
	Disposal of other MBT outputs
	RDF quality may degrade in long term storage

What are the specific challenges and advantages of MBT with AD technology?

Advantages	Challenges
Diversion from landfill	Need for an acceptable disposal route for the digestate
	Whether or not the digestate can be used as biomass rich solid if dried as another fuel output
Increase in recycling	Odour emissions
Heat and power generation from the biogas may attract a premium price if it is eligible for support as part of national renewable energy support programmes	Comprehensive pre-treatment is necessary to avoid contaminants (plastics, etc) in the digester
Production of an energy carrier which can be used when and where needed	Gas handling, storage and clean-up required
	Requires skilled staff to operate digester
	Requires treatment of large quantities of water if wet AD process

MBT 1: MBT with RDF production and composting

This is shown as option C in Figure 45.

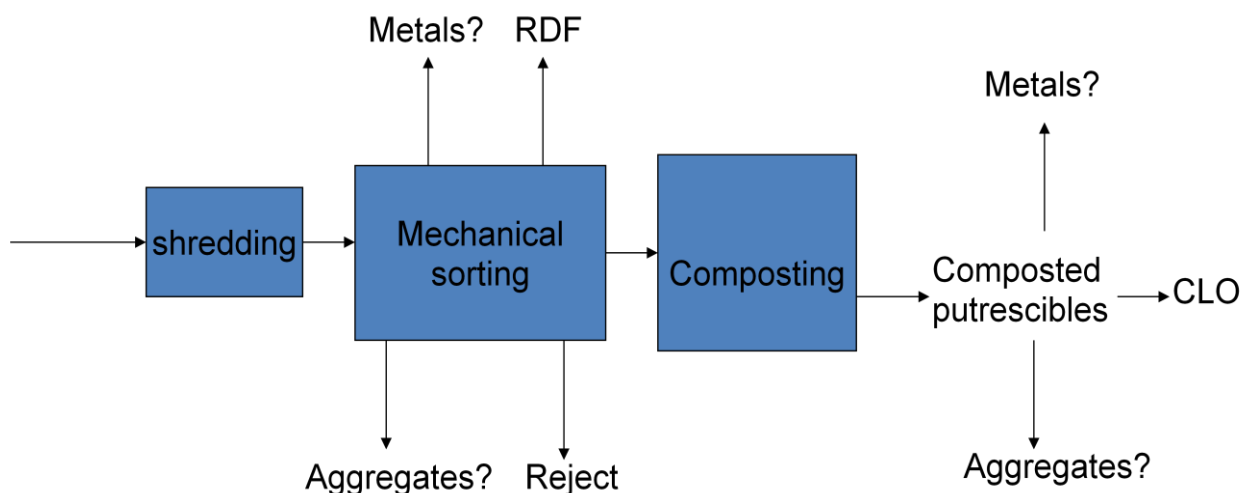
What are the main components of an MBT producing RDF?

Figure 46 shows a schematic representation of an MBT plant designed to produce a solid fuel residue, RDF. In a typical configuration, the incoming waste is shredded to some extent and the dry combustible fraction (plastics, paper, card, wood and textiles) are screened off from the bulk of the waste as the RDF. The RDF therefore comprises the driest and most combustible components of the waste as received. Depending on the composition of the feedstock, the RDF fraction may account for up to 40 - 60% of the input feedstock mass. The initial separation may also recover metals and aggregates as recyclable products.

The residue from this separation may then be composted for an extended period of several weeks to stabilise the residue for landfill. The stabilised material may be refined to produce a compost-like output (CLO), which may be used for land restoration under licence if it is of acceptable quality. This refining may generate additional recyclable materials, such as metals and aggregates. The total amount of these recyclables might be about 5 - 10% of the input mass.

There are options where the composted residue is dried during the composting stage and the composted material used as a low grade fuel. In the UK there are trends to examine the potential for refining the residue to derive a fuel with sufficiently high biomass content for this material to be considered as a bioenergy fuel for the Renewables Obligation, if removal of plastics is efficient.

Figure 46: Schematic of MBT with RDF production and composting (“?”) Represents optional processes where the materials recovery may change depending on the technology)



End use of the main RDF output of MBT

The RDF produced is typically of large particle size and low density with a net CV in the range of 10 - 14 MJ/kg, which is typically higher than the feedstock waste. Where and how RDF is used varies, but it is more commonly being considered as a fuel for power plants (i.e. co-incineration with fossil fuels, where the plants can meet WID emission limits) and in dedicated RDF combustion plants. The calorific value of this material is too low for use in cement kilns. RDF is not considered as a high grade fuel product and although the impurities are not often monitored, there seems no real barrier for its use in incineration or other thermal processes that would accept MSW.

It is worth mentioning that interest has been shown in innovative solutions for the use of RDF in other thermal processes, such as gasification and pyrolysis for the production of liquid fuels, as well as syngas.

The country where MBT has been used most extensively is Germany. Here, a number of options have been developed. One major issue facing the German plant operators has been the market for the RDF and the UK is currently in a similar position. Several planned MBT facilities currently in procurement also have to procure the associated RDF using EfW plant to ensure a market for the RDF.

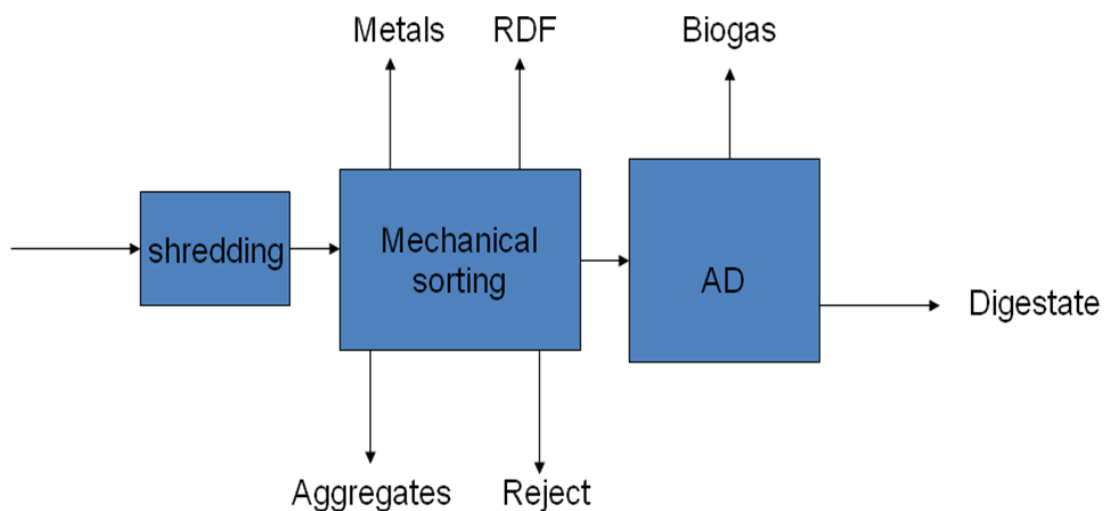
MBT 2: MBT with RDF production and anaerobic digestion (AD)

This MBT configuration is similar to the above in that there is the same initial mechanical step producing an equivalent RDF material, which also amounts to 40 - 60% of the input feedstock mass. The key difference is that the organic rich putrescible fraction is anaerobically digested rather than composted. This has the advantage of producing energy from both the dry combustible fraction as RDF and from the wet putrescible fraction as biogas. This MBT configuration is probably the most popular configuration being implemented in the UK, partly due to the promotion of AD by Defra in recent years. Shown as option A in Figure 45.

What are the main components of an MBT configured to produce biogas?

Figure 47 shows a schematic representation of an MBT plant configured RDF and biogas production.

Figure 47: Schematic of MBT with RDF production and anaerobic digestion



Biological treatment

In these MBT plants, the anaerobic digestion process involves the break down of the separated biodegradable matter (food and garden waste) by micro organisms in the absence of oxygen. In most MBT systems, the separated putrescible fraction undergoes an extensive preparation to remove inert material and sand from the AD feed. This is because these impurities may build up and block the tank stirrers or other movable parts or gas outlets. The end product of the biological process is a methane and carbon dioxide rich gas (usually called 'biogas') and an un-stabilised nutrient-rich solid digestate that could be used as a soil amendment in some soil restoration activities, or composted further to produce a stabilised compost for land restoration. The digestate may also be dried by waste heat from the biogas

combustion and used as a low grade solid fuel. Unfortunately, in many cases, the markets for the digestate are not realised and the digestate may have to be landfilled,

Several different AD process configurations exist for the biological vessel (the anaerobic digester): they can be operated as batches or continuously, at mesophilic (30 - 40°C) or thermophilic (60 - 70°C) temperatures, at low (wet digestion) or high solids content (dry digestion) and with varying complexity (number of stages/vessels). The design of the plant will need to be suitable for the organic material that is digested, particularly the feedstock handling and transfer equipment. The typical composition of biogas is: methane, CH₄ 50 - 75%; carbon dioxide, CO₂ 25 - 50%; nitrogen, N₂ 0 - 10%; hydrogen, H₂ 0 - 1%; hydrogen sulphide, H₂S 0 - 3 Oxygen, O₂ 0 - 2%. There are currently no gas quality standards specifically for biogas; however, given the deleterious minor constituents of raw biogas, such standards may be developed in the future. Safety standards are developed for land fill gas and sewage gas that are produced by the same microbial processes and it is likely that, as MBT including biogas becomes more common, such standards will be applied here as well. Further information on the use of anaerobic digestion in waste treatment is available from IEA Bioenergy Task 37, which examines the use of anaerobic digestion.

End use of the main output of this type of MBT

MBT is an intermediate treatment technology and a viable end-use is needed for biogas, the main output of the MBT presented here. The main alternatives for energy recovery from the biogas are:

- heat and electricity production with a engine or turbine (for higher quantities of biogas) for internal use (digester, buildings);
- supply of heat and/or electricity to the grid (biogas is a renewable energy carrier and its use may be supported in some countries);
- upgrading (removal of pollutants, especially H₂S) and concentration in order to be used as a vehicle fuel;
- upgrading to allow injection directly into the natural gas grid.

Solid residue

As indicated above, in addition to the production of biogas, the anaerobic digester also produces a solid humus-like material, which is termed 'digestate'. Currently, most MBT processes do not produce a digestate that can be sold commercially for compost or soil conditioning. However, if the digestate is treated after anaerobic digestion, then part of the residue may be post-composted to produce a soil conditioner, and a fluff high in calorific value and suitable as an RDF may also be produced.

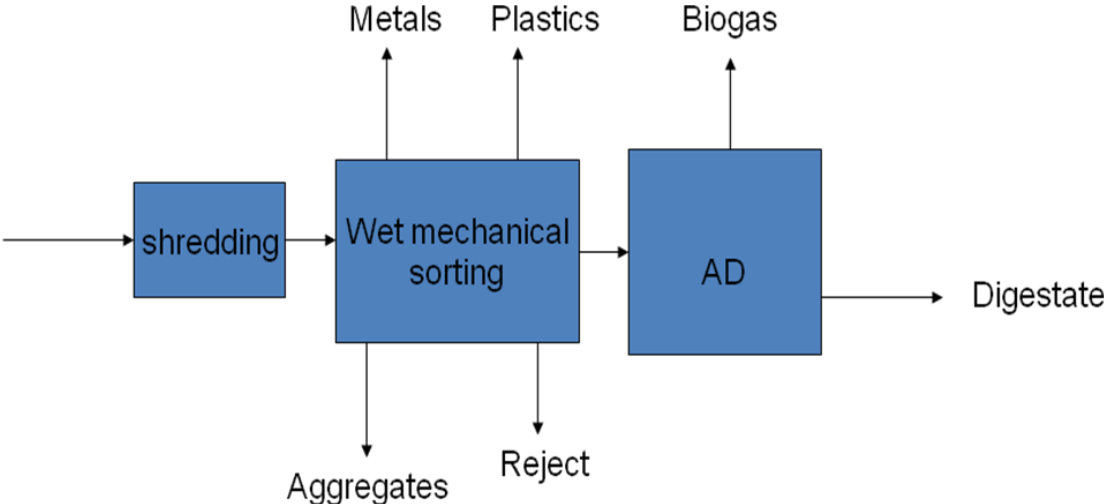
MBT 3: MBT with anaerobic digestion and recyclate production

This is an MBT configuration that differs significantly from the above AD concept and is a rarer and more novel approach. Plants exist in Israel and Australia and at least one plant is under construction in Scotland. In this design, the waste is first mixed with water and undergoes a mechanical wet separation process. During this separation process most of the biodegradable waste is macerated into a sludge and the recyclables, such as metals and plastics, are then removed and washed as clean recyclates. The remaining sludge is then AD treated.

The key difference is that the process produces all the plastic as a clean recyclate which can be recovered, although its use as a high CV fuel is possible. Also, the sludge for digestion contains the paper and card biomass as well as the putrescible food and green waste. Because of the presence of the less biodegradable paper and card, the biogas yield per tonne of organic matter is less than the conventional AD concept although, overall, more biogas is actually produced because the whole biodegradable fraction is sent to the AD stage.

As with other AD concepts, the digestate may be dried and used as a high biomass content fuel, or it may be applied to soil or composted prior to applying to soil in some soil restoration activities, if of suitable quality

Figure 48: Schematic of MBT with anaerobic digestion and recyclate production



MBT 4: MBT with biodrying and SRF production

In this MBT configuration, the waste is first shredded and then the whole waste is composted for a short period of 2 to 4 weeks. This composting is carried out using a forced aeration system where air is forced through the composting pile at a high rate. The combination of forced aeration and heat generated by the microbes as a result of their aerobic composting activity results in significant drying of the whole waste.

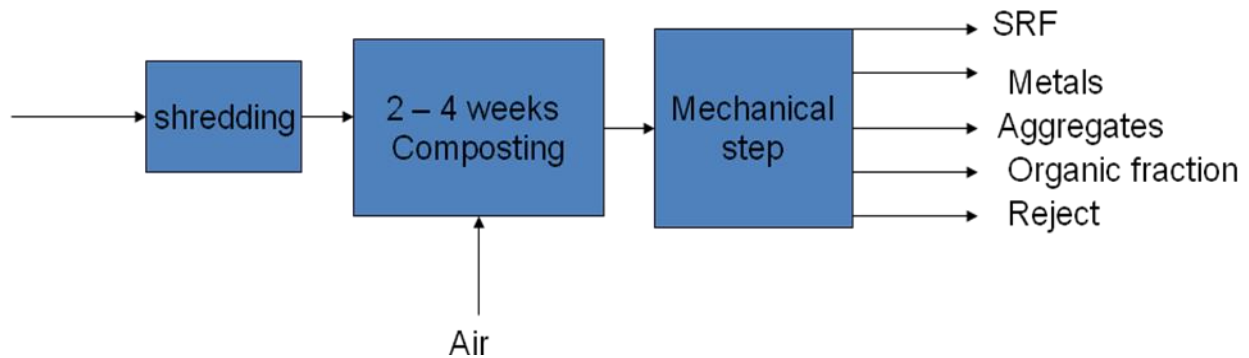
The biodried waste is then subjected to the main mechanical step which typically would produce a SRF fuel, recyclate metals and aggregates and a reject material for landfill. The solid fuel in this case is termed an SRF because it will have been derived from a more extensive processing than the RDF produced in the earlier discussed MBT configurations.

The biodried material may be processed to give several qualities of SRF. For example, it may be processed to yield an SRF with a high plastic to biomass ratio, which would have a corresponding high CV of 15 - 20 MJ/kg which would be suitable for use in cement kilns. However, the yield of this material would be low (20 - 30% of the feedstock mass). Some of the residue from such a process might be used as a lower grade solid fuel, as it would still consist of a dry biomass rich material. Alternatively, the biodried material may be processed into a larger yield of lower CV product where as much as 60% of the input feedstock may be delivered as an SRF with a CV in the range 10 - 15 MJ/kg.

Designation of the solid fuel product as an SRF, rather than a RDF, is beneficial as the SRF is considered as a more stable and tradable commodity. Various CEN standards have been developed to analysis and categorise the quality of SRF and a quality management system has been developed to compliment this to provide assurance of a consistent quality of the SRF as a tradable fuel. In the UK, SRF complying with the CEN standards may attract a full 2 ROCs for the biomass fraction if used in a certified CHP plant, which also provides a financial incentive for this product.

Several MBT plants are in operation in the UK with several more planned.

Figure 49: Schematic of MBT with biodrying and SRF production



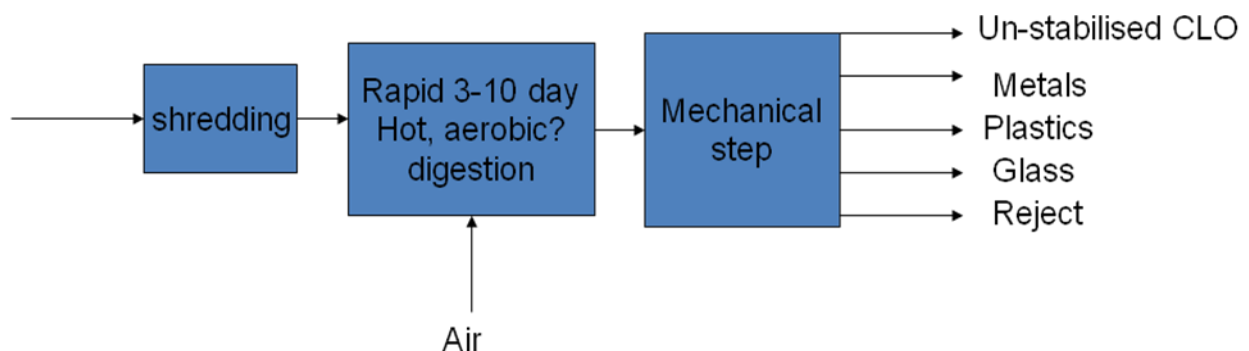
MBT 5: MBT with rapid composting and recyclate production

This MBT configuration is only applied in a few examples and consists of a very rapid initial composting phase at high temperatures for as short as six days in a reactor that mixes and churns the waste. The combination of mechanical attrition and rapid hot composting breaks the biodegradable matter down into a small particle sized fibre. This fibre is easily separated from the other waste components during subsequent mechanical processing.

Typically, the process would be designed to produce recyclates such as plastics, metals and glass and an organic rich biomass fibre. The fibre has a high biodegradability and requires further composting if it were to be considered for recycling to land. However, it may also be used as feedstock for AD or dried as biomass fuel. It might also be possible to use the plastics as a high CV fuel.

One supplier offers both the recyclate/compost option and the solid fuel option (with or without AD) option.

Figure 50: Schematic of MBT with rapid composting and recyclate production



MBT 6: MBT with biostabilisation

In the MBT with biostabilisation, the whole waste is composted for an extended period of several weeks to remove as much of the biodegradability of the waste as possible prior to landfilling the whole residue. In its original form this process provides minimal recyclate in the form of metals and perhaps some aggregate and plastic recovery, as these materials are more easily separated from the biostabilised waste. A few processes designed around this MBT configuration have been planned but with the increased cost of landfill due to the landfill

tax increases, approaches are being considered to produce fuels from the biostabilised waste.

In this configuration, a high CV fuel might be produced from the separation of a plastic rich combustible fraction. It has also been proposed that a biomass fuel attracting maximum ROCs could be produced by refining the residue.

Whilst this is an unproven concept in the UK, it might have some attraction in that the biostabilisation would at least treat the waste for landfill and if opportunities for markets for fuel were realised, then the same MBT technology could be adapted to produce the fuels.

Figure 51: Schematic of MBT with biostabilisation

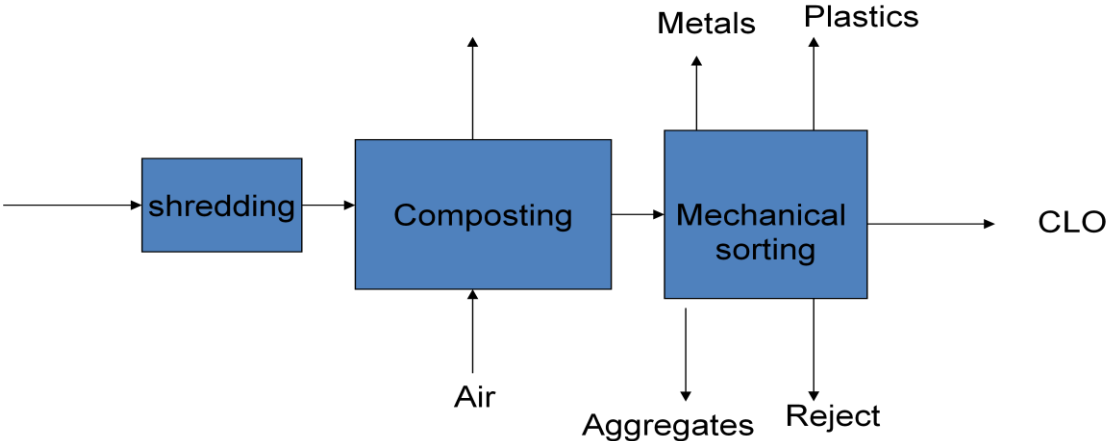


Table 7: Summary of main energy product streams from various MBT configurations

MBT generic design	RDF production	SRF production	Biogas energy by AD	Recyclables
MBT with RDF and composting	Yes - typically 40 - 60% of input	No	No	Yes - metals and aggregates
MBT with RDF and AD	Yes - typically 40 - 60% of input	No	Yes - from typically 40% of input	Yes - metals and aggregates
MBT with AD and recycle	No - but recovered plastics might be used as fuel	No	Yes - from typically 60 - 70% of input	Yes - metals, aggregates and plastics
MBT with biodrying for SRF	No - solid fuel is SRF	Yes - amount and quality is controlled. Typically 20 - 50% of input	No	Yes - metals and aggregates
MBT with rapid composting and recycle	Not normally, but possible in some configurations	No	No	Yes - metals and aggregates
MBT with biostabilisation	Not normally, but possible in some configurations	No	No	Yes - metals, aggregates and plastics

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Dec 2002, Hong Kong SAR

MSW incineration facilities worldwide

EU-27

Number of installations: about 420 (2008)

Total capacity: 200 Mt/y

Average capacity MSW incinerator: 200,000 t/y

Waste incineration market: 90% grate

Specific features: about 390 installations are to be found in the EU-15 countries

Japan

Number of installations: about 1,700 without energy recovery and 180 with energy recovery (the latter representing about 44% of the total capacity); the 400 largest installations represent about 73% of the total capacity (2004)

Total capacity (for the 1,880 installations): 70 Mt/y

Waste incineration market: about 80% grate (in number) and 7-8% FB (of the 400)

Specific features: about 75 of the approximately 120 gasification plants in the world are located in Japan (2008)

Canada

Number of installations: seven main (i.e. greater than 25 tpd capacity) – five with energy recovery and two without (2007)

Total capacity: 1.63 Mt/y

Specific features: 2% of the waste collected (residential and non-residential) are thermally treated and 76% are landfilled. The throughput is about 763 000 t/y, i.e. there is a large overcapacity

USA

Number of installations: 87 EfW plants in 25 states (2007)

Total throughput/capacity: 28.7 Mt/y, EfW are operated in excess of 90% (2007)

Specific features: (1) 1/5 of US MSW incinerators use RDF; (2) about half throughput is in the Northeast

China

Number of installations: about 47 (2009)

Total capacity: 11.2 Mt/y

Specific features: fast development (only 30 plants in 2002)