

TNO-report

Inventory of international Municipal Solid Waste Incineration Technologies

Reference number 93-387
File number 112326-24075
Date November 1993 (May 1994)
NP

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Keywords
— municipal solid waste
— waste incinerator
— incinerator technology
— inventory

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Prepared for
the Netherlands Agency for Energy and the
Environment and the National Institute of Public
Health and Environmental Protection.

Summary

In this report a review is given of the state of the art and the developments of MSWI (Municipal Solid Waste Incineration) technologies. Also the situation in some characteristic countries is discussed.

The most applied technology for MSWI at larger capacities is the grate incinerator. It appears that the type of grate is not significant with respect to combustion performance and emissions. The design of the combustion chamber and air injection geometry however is of utmost importance. These features are meant to give a high mixing intensity to the combustion process in the gaseous phase. By measures like flue gas recirculation the NO_x formation can be suppressed.

The quality of the waste (especially moisture content), as fed to the process, varies considerably in time. This requires a good process control system. Essential parts of such a system are: monitoring of flue gas components, monitoring the location of the fire, control of primary/secondary air ratio etc.

Equipment suppliers devote a lot of development activities on improving the design of the combustion chamber. Sophisticated process control systems gain more attention.

Of other incineration technologies only the Fluidised Bed Combustor (FBC) is used to a certain extent, mainly in Japan. The main disadvantage of a FBC is that the bottom-ash, because of the low temperature of the process, is less inert than that from a grate firing system; also FBC produces relatively more (less inert) fly-ash. An important advantage is its insensibility to variations in composition and calorific value of the waste. Also waste with a very high calorific value (for instance plastics) can be processed.

With the conventional boiler tube materials the steam conditions are limited to approx. 40 bar and 400 °C. There is a tendency to go up to steam temperatures of 500 °C by applying higher alloy materials; this may increase the efficiency with 3% points.

The present severe environmental standards require an extensive flue gas cleaning system. An often applied flow scheme, in countries with the most stringent emission standards, like The Netherlands, consist of: Electrostatic Precipitator (ESP), two stage wet scrubber, active cokes system, de NO_x reactor (SCR).

The application of active cokes is still under development. It can be used in different reactor types (fixed bed, entrained flow, fluid bed) or added to the wet scrubber liquid, in combination with a fabric filter.

A novel development is the combined NO_x /dioxins removal in an SCR reactor.

Flue gas cleaning produces several residue flows. Normally these residues cannot be landfilled without additional treatment. For bottom-ash and fly-ash several processes are under development or in the demonstration phase. Most processes require relative high investment and energy costs, i.e. melting processes may require around 25% of the electricity produced from the incineration process.

In case of scrubber residues the problem is to recover salts with a low content of impurities, which can be applied. Also many processes are still in the phase of development.

Contaminated active cokes has to be destroyed by combustion. At present there is positive experience with combustion in rotary kilns.

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In this report the municipal waste conversion situation in Germany, the USA and Japan is described. In all these countries the share of combustion is still growing. However the environmental requirements and consequently the additional abatement technologies are in a different stage.

In (Western) Germany around 50 relatively large waste incineration facilities with a total annual capacity of approximately 11 Mtonnes are in operation, all with energy recovery. There is still a strong public opposition against the expansion of the incineration capacity, although the recently introduced very stringent environmental standards that have to be met, might change this attitude in the near future. The German waste incineration technology is at an advanced stage. Several active cokes filter installations are in operation. New developments like catalytic oxidation of PCDD/F are in the demonstration phase.

In the USA the present environmental standards are less severe than in Germany and only apply to the larger installations. In total, around 35 Mtonnes per year is incinerated in approximately 190 facilities of various size and design, mostly with energy recovery. Characteristic is the broad application of spray dryers for flue gas cleaning. Apparently landfill of the larger volume of semi-dry scrubber residues is not a bottle neck.

In Japan around 1900 incinerators are in operation with a relative small size (50,000 tons/a). Besides moving grate systems, over 100 fluid bed combustors (FBC) are in operation. These FBC/s are mainly in the smaller capacity range and intended for 2-shifts operation (13 - 16 hours per day). Almost all incineration plants are equipped with energy recovery facilities. Energy is used for heating purposes. Generation of electricity hardly takes place.

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1 Introduction

In this report the state of the art of municipal solid waste incineration in various countries will be reviewed. Emphasis will be on the identification of the most advanced systems being applied or developed in various countries. Little attention will be paid to the 'systems of yesterday', although at present most existing installations might be characterised as such. It has been compiled from a different point of view than two other known recent reviews of waste incineration, i.e. the report being compiled by the International Ash Working Group (to be published shortly), that concentrates on incineration residues, and the Dutch Handbook 'Quality control waste incineration' (Kwaliteitsbeheersing afvalverbranding [12]), that presents a technically detailed description of systems and components.

This review has been made under contract of Novem (Netherlands Agency for Energy and the Environment) and RIVM (National institute of Public Health and Environmental Protection).

In the developed world, parallel to the economic growth, municipal solid waste generation has been rising to a level of around 1 kg per day per capita. This is of growing concern, not only because of material and energy losses associated with the disposal of this waste, but specially because of the environmental effects of the most widely used disposal options.

Incineration of Municipal Solid Waste started off in the 19th Century as a means of sanitation to reduce the threat of uncontrolled dumping of waste to the public health and odour reduction. Later, another reason was reduction of the volume of waste to be landfilled, and thereby minimizing the disposal costs. At present these are still the main reasons for waste incineration. However many other considerations have grown more and more important, changing drastically the waste management policy and technology.

Generally, minimisation of the negative environmental impact of the waste management strategy, 'not entailing excessive cost' is an accepted guideline. It will be clear that there are a lot of different opinions on the cost level that is acceptable, and also on the question how to compare various effects e.g. air pollution vs ground water pollution. This is reflected in the large variation in the actual waste disposal policies and the related legislation in different countries.

There is however a growing consensus regarding the priority order of the options to handle the waste problem:

- Prevention of waste generation;
- Reuse for the same purpose/materials recycling;
- Reuse for a lower grade purpose;
- Thermal conversion (usually incineration), using the energy content of the combustible material;
- Landfilling of non combustible material and residues from incineration.

The actual situation in many countries is still quite different. In nearly all countries, landfilling is the most important waste disposal route. Apart from some specific components (e.g. paper, glass), recycling rates are still rather low. In case of incineration many installations are operated without energy recovery.

The reason for the large part of MSW being landfilled is, that it is usually the cheapest option as long as there is sufficient space available. In a number of more densely populated countries (i.e. Japan, Netherlands) this already appears to cause problems. In other countries this will cause problems in the near future, enhanced by more stringent requirements for getting a permit to open new landfill sites and opposition from the public.

Although it is generally recognised that prevention of waste generation and recycling of materials from the waste stream are the preferred options to reduce the quantity of waste to be disposed of, this approach requires a fundamental change in production schemes and consumer behaviour, which are both autonomous and therefore relatively slow processes, usually without a strong economic incentive.

Waste management policies and the related technologies, as far as incineration schemes are concerned, can be ranked from simple to the most sophisticated by taking into account how many of the subsequent aspects have been incorporated in the respective policy/technology. Such a ranking could be:

- Volume reduction
- Energy recovery
- Material recovery
- Reduction of acid gas emissions
- Reduction of organic trace components
- Reduction of heavy metals emissions
- Upgrading and recycling of residues
- Minimisation of waste water discharge (up to zero discharge operation)
- Inertisation of solid residues
- Fuel pre-treatment

In the next chapters these items, as far as these are directly related to incineration will be elaborated in connection with practical applications or development work in various countries.

2 Incineration technologies

For MSW Incineration, mainly grate incinerators of various designs and sizes are applied all over the world. Other systems like rotary kilns, fluidised bed combustors and some special designs are at present limited in number and are usually applied under special circumstances or for specific waste streams. However, because of potential changes in waste management, e.g. increasing processing of MSW to RDF, changing composition of the waste or requirements concerning the residues, the market share of the various systems might change in future. The characteristics of the most important systems will be given below.

2.1 Grate incinerators

In this type of incinerator the grate acts as the platform on which the subsequent combustion phases take place during the transport of the waste from the inlet to the last section where the (bottom)ash drops off. Primary combustion air is supplied in a controlled way through the grate.

2.1.1 Grate design

The grate elements are designed to transport the waste and to mix it to get a proper burnout of the residues. Characteristic data for a grate are presented in Table 1.

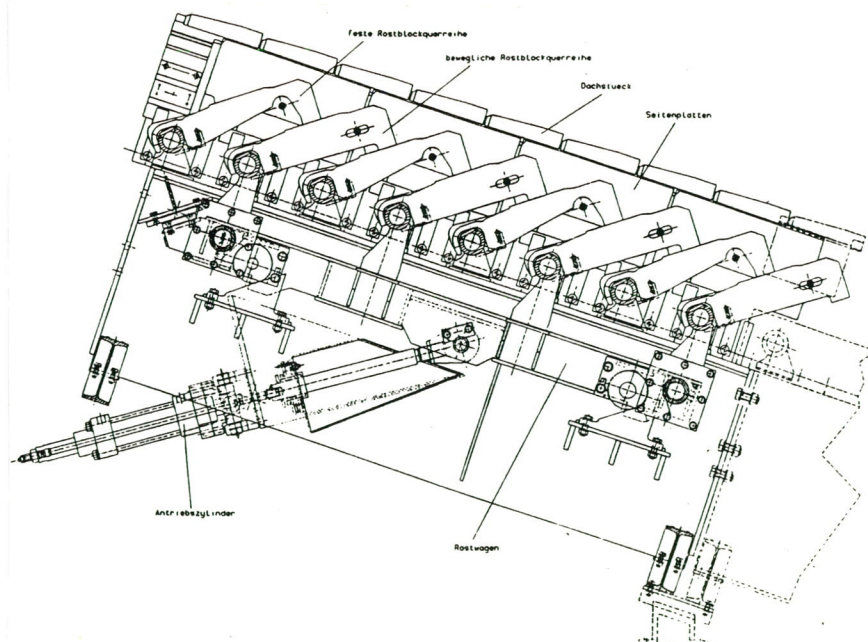


Figure 1 Von Roll grate system

Table 1 Characteristic data of a MSW incinerator grate

Height of waste bed layer	0.1 - 0.5 m
Dimensions : Length	8 - 15 m
: Width	3 - 10 m
Grate surface area (max)	appr. 100 m ²
Capacity	4 - 30 Mg/h (ton/h)
Inclination	up to 30 degrees
Number of air stages	3 - 5
Width of air slits in the grate	1 - 3 mm
Air entrance surface area in grate	1 - 5%
Effective material transport speed	< 0.1 m/s
Specific load	1.8 - 3 GJ/m ² h
Power consumption	< 3 kWh/Mg (kWh/ton)
Air discharge speed from slits/nozzles	5 - 70 m/s
Gas velocity : in bed	< 1 m/s
: above bed	1 - 5 m/s
Pressure drop over grate/bed	5 - 10 mbar
Air supply temperature	25 - 150 °C
Volatiles ignition	220 - 320 °C
Solid material ignition	300 - 400 °C
Cracking start	600 °C
Char ignition	750 - 850 °C
Ash weakening start	850 - 1000 °C
Residence time solids	0.3 - 1.5 h
Fly-ash part of residues	10 - 25%

The different grate designs that are applied at present can be divided in a number of categories:

Reciprocating grate

This grate, existing in quite some variations, basically consists of an assembly of rows of stationary and moving grate bars. By the action of the moving bars, either forward or reverse, in combination with the slope of the grate, the waste is mixed and transported. Combustion air is fed to the waste through slits in the bars. This allows for a proper control of the primary air supply, because the air discharge area is little effected by wear of the elements. Process control is enhanced by dividing the grate in various, independently controllable sections. A disadvantage of this system is the large number of moving parts subject to wear. A number of systems from various manufacturers is presented in Figures 1, 2 and 3.

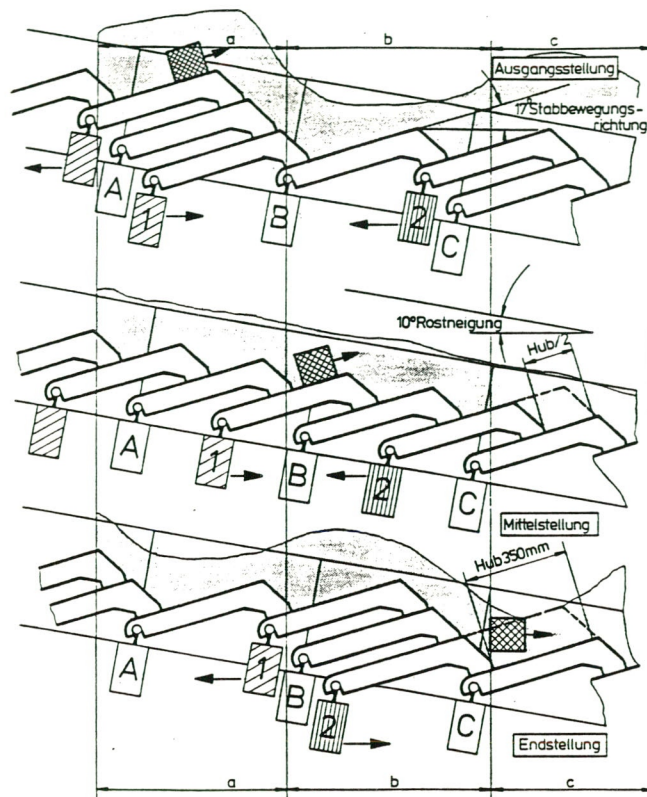


Figure 2 Deutsche Babcock grate system

Roller grate

Basically this is a rather uncomplicated design (Figure 2), allowing good control over the waste transport speed, although mixing is not ideal. Air is entering the waste bed through slits in the rollers and along the scraper plates, that have to prevent waste from falling down between the rollers. Because the gap between plate and roller is subject to wear, distribution of the air flow may change with operating time, causing less air passing through the rollers, or too much through the gaps. This off-design airflow has to be prevented, because it will have a negative impact on the combustion process.

A clear advantage of this type is the long lifetime of the rollers, caused by the relatively low thermal and mechanical load; only the small upper part of the rollers is exposed to the high temperature of the combustion chamber, leading to a low average metal temperature.

Travelling grate, rocking grate

These two systems are less used for new installations because they do less satisfactory fulfill both requirements simultaneously, i.e. transport control and mixing of the waste.

The travelling grate (Figure 5), consisting of a closed conveyor belt is sometimes used as a first stage of a grate to control the waste feed.

The rocking grate consists of overlapping plates (Figure 6), pivoting at one side to mix the waste.

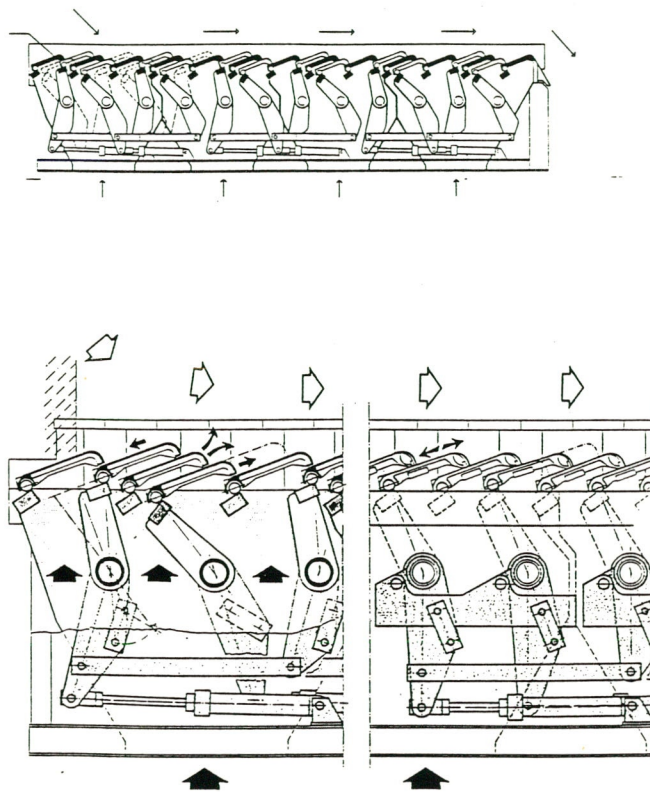


Figure 3 W&E grate system

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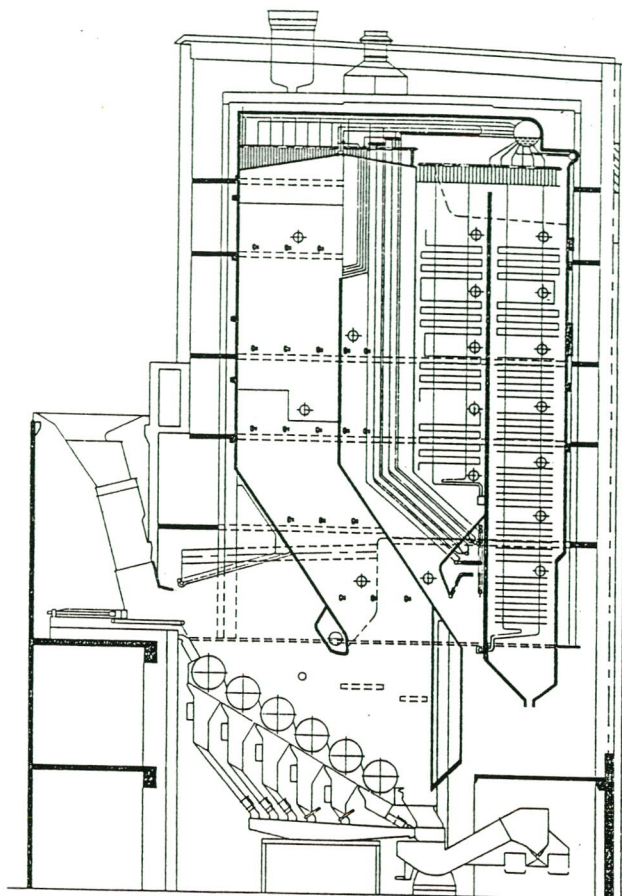


Figure 4 Roller grate system

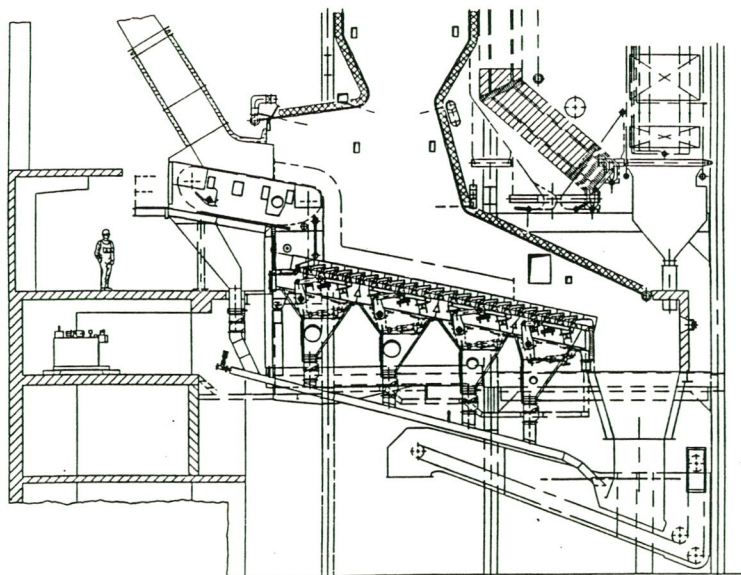


Figure 5 Travelling grate system

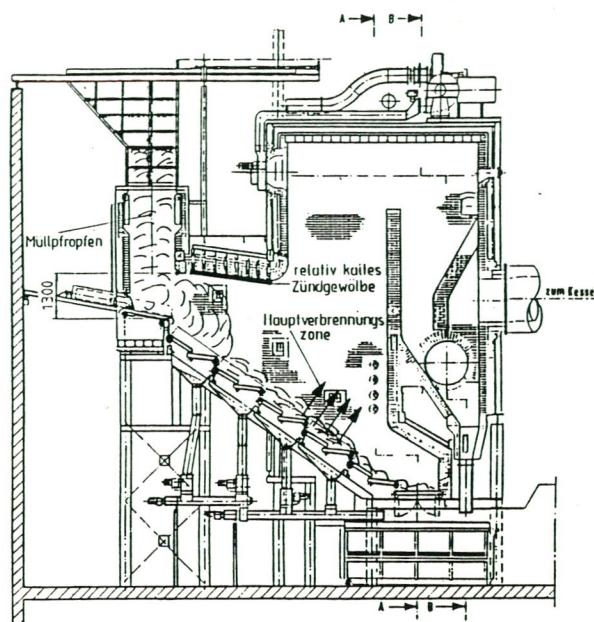


Figure 6 Rocking grate

2.1.2 Incinerator design

Basically, incinerators can be divided in three categories, depending on the geometry of the combustion chamber in relation to the grate (Figure 7):

- parallel flow, where the combustion gases are guided more or less parallel to the process, entering the freeboard near the end of the grate;
- counterflow, the entrance to the freeboard is above the first part of the grate;
- intermediate flow, the entrance to the freeboard is approximately above the middle section of the grate.

These designs all represent different compromises between the various requirements that should be fulfilled in this very important part of the incinerator:

- sufficient high temperatures and residence time to destroy most of the volatile organic components in the waste and get a proper burn-out;
- limited wall temperatures to prevent slagging;
- high combustion efficiency;
- prevent entrainment of particulates into the freeboard by avoiding high local velocities;
- create sufficient turbulence to promote an even distribution of combustion gases (velocity, temperature, concentration) at the entrance of the freeboard, so that it is assured that undesired conditions (e.g. low O₂ content, extreme temperature) do not exist locally.

The main problem encountered in trying to comply with these requirements is the fact that the 'fuel' is very non-homogeneous and will therefore show a considerable variation, not only in time, but also over the grate surface. The first possibility to work on this problem is to mix the waste in the bunker as good as possible before feeding

it to the incinerator. Usually this will not be sufficient and there are a number of parameters that have to be controlled, in order to optimise the process.

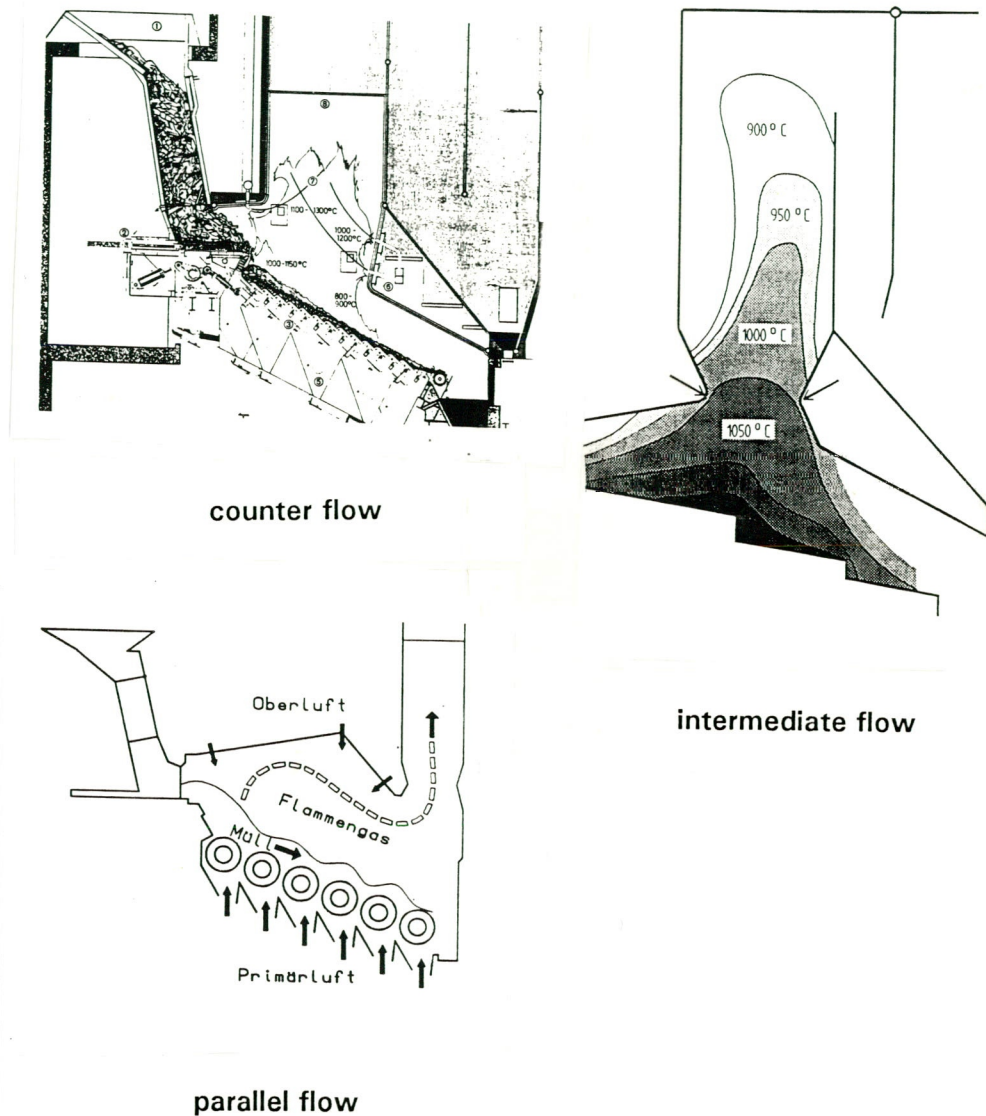


Figure 7 Combustion chamber design

2.1.3 Process control

The main parameters to control the combustion process are the feedrate, the total primary air supply and, if the required provisions are available, the distribution of this air to various sections of the grate. Other variables are the speed of the various sections of the grate, preheating temperature of the combustion air or

the secondary air supply. Apart from the fact that the determination of the optimum setting of all variables is not always straightforward, an important condition that should be met is that sufficient information on the process parameters (temperature and O₂ content) is available.

The burning of the waste on the grate can be divided in five characteristic stages: drying, volatilization, ignition, combustion and burn-out.

At first the waste is dried and slowly heated. The heat used for this is mainly supplied by radiation from the flames and the walls of the combustion chamber. Sometimes the primary air, which is supplied through the grate, is preheated (up to 120 °C), which speeds up the drying process considerably.

In the second stage gases evade from the waste and, at temperatures above approximately 400 °C, the gases ignite (third stage) and react with the supplied oxygen (mainly through primary air, in this stage).

In the next stage, combustion of the solids takes place, which is completed on the last part of the grate (burn out/glowing).

Each of the stages mentioned above, requires a different amount of primary air and different residence times because of different reaction times. Therefore modern combustors can supply primary air in different amounts to each zone of the grate and can adapt the ratio between primary and secondary air. A typical air distribution [1] is 40% secondary air and 60% primary air of which 10% is used for both the first and the last stage. Also the speed of the grate per zone is variable.

The main challenge in the control of the combustion process is to react quickly to the changes in the composition of the feed. This requires a control system which can rapidly adjust the supply of air and the speed of the grate to the changing feed. Evidently, as the waste is not continuously analysed prior to combustion, other indicators are needed to inform the control system on e.g. an increase in the heat content of the waste or the need for more air in a certain zone.

Just until a few years ago the main indicator was the steam production rate: if the production decreased, more waste was fed to the grate and if the production increased less waste was supplied. The supply of air was then varied proportionally. Sometimes the temperature of the rear-wall was used to determine the grate speed: if the temperature got too high, this was an indication that the fire moved too far to the end of the grate, with high risk of incomplete combustion. Then the speed of the grate was slowed down. This way of control, however, is neither very accurate nor quick, resulting in unstable combustion and high emissions of CO, NO_x and unburnt organic compounds (precursors for PCDD/F).

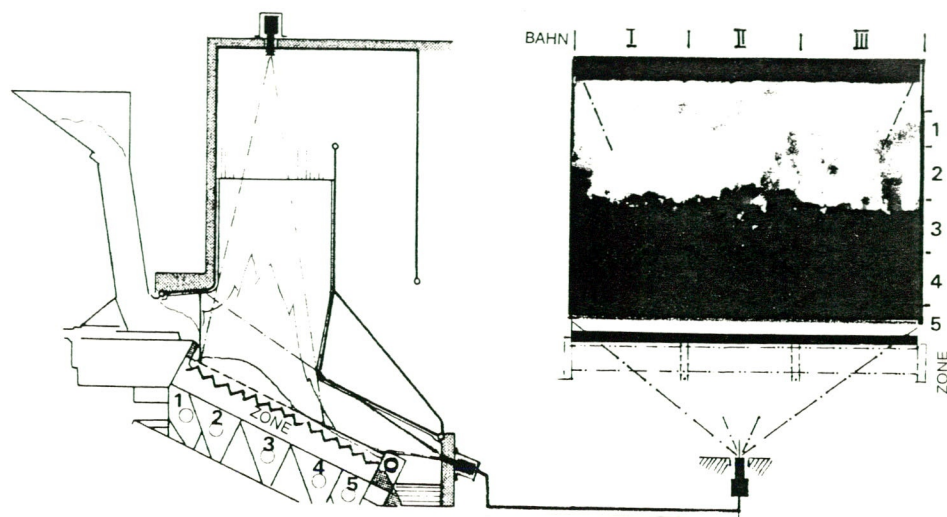


Figure 8 Infrared fire monitoring

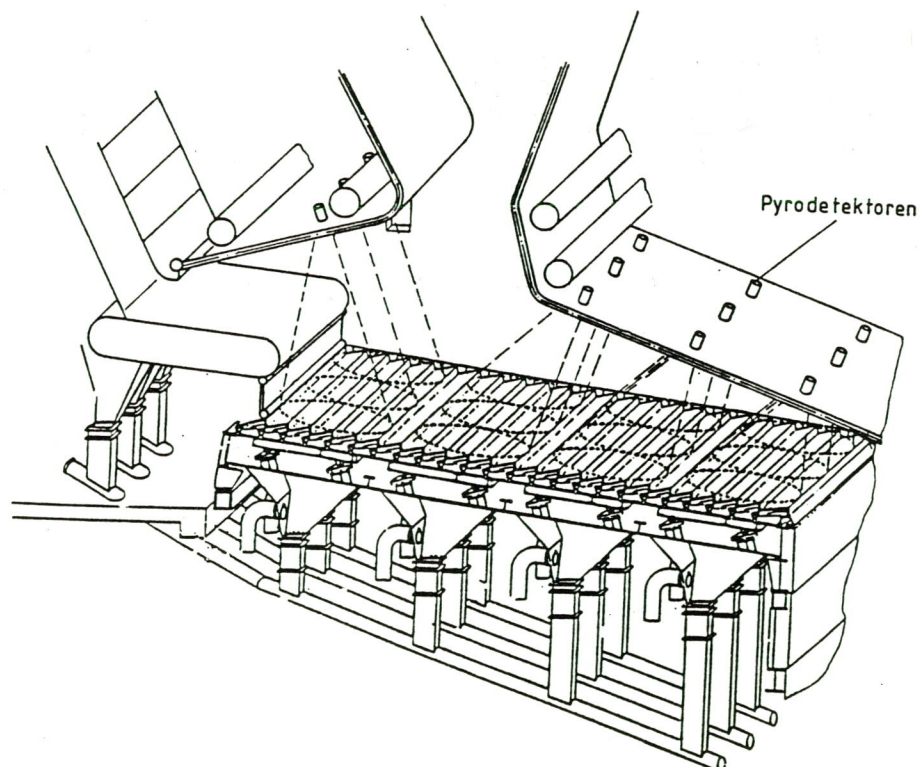


Figure 9 Pyrodetector monitoring

Today modern combustors at least monitor CO, O₂, air flow and temperature, apart from the steam production rate. Some systems go further and use techniques like infrared monitoring (Figure 8) of waste layer temperatures [2] or monitoring of H₂O- and CO-concentration above the layer by pyro-indicators [3] (Figure 9). By measuring the temperatures, the waste feed and transport rate can be adjusted to keep the fire on the desired location on the grate. The supply of primary air also is based on this information.

Pyro-indicators measure water in the front part of the grate to establish the moisture content of the waste. As this is the component in the waste which is strongly related to the heating value and can be monitored with a minimal delay, the moisture content gives good information on fluctuations in the heating value of the waste. This information then is used to control the supply of primary air.

In the middle of the combustion chamber, the CO-content is measured to give information on which the supply of secondary air can be based, and at the end of the grate the burn-out of the bottom-ash is monitored. The latter is done by giving a pulse of air to the waste. If a flame occurs, this indicates that there still is combustible material in the bottom-ash. More air then can be added to this spot until no combustibles are left. Finally also the concentration of radicals in the gas phase is measured to see if the combustion has been complete. Injection of secondary air can be used to supply extra oxygen, at the same time improving the mixing of the flue gases, which may be even more important.

These techniques (infrared monitoring/pyro-indicators) are very new and only applied in very few installations [2, 3] so far, with good results as to combustion completeness (according to the manufacturers of the systems).

2.1.4 Air supply

The supply of air is very important to the overall performance of the combustor.

With respect to emission control, it has been shown to be advantageous, to combust the waste with as little air as possible. It appears that the emissions of NO_x, particulate matter and PCDD/F are less when the excess air amount is reduced to a certain extent [2, 4, 5, 6, 7]. Below excess air levels of 1.3 - 1.4 the CO-emissions starts increasing again. To keep the CO- (and the unburnt hydrocarbon) emission low at minimal air ratio's, flue gases should be very well mixed (secondary air, furnace geometry).

The additional supply of oxygen through the secondary air ports can give rise to higher NO_x-emissions, if the temperature (locally) is very high (> 1100 - 1200 °C). To prevent this, recycled flue gases can be injected instead of air: less oxygen with the same mixing impact. This is currently being demonstrated in a number of installations. The main problem with this method, specially in retrofit situations, is corrosion in the flue gas recycling system [5].

When energy recovery is considered, a decrease in the amount of flue gas causes an increase in the energy efficiency of the boiler.

In addition to that, the size of the boiler and the flue gas cleaning system also decrease proportional to the flue gas flow.

It may be concluded that the amount of combustion air should be minimized to the point below which, through local lack of O₂, CO and hydrocarbons are not completely burnt any more and this cannot be compensated by increasing the mixing intensity. This mixing is largely effected by the geomtry of the boiler, which is therefore a very important design aspect.

In practice this means that modern combustors with a high mixing intensity are operated with excess air ratios of 1.6 - 1.8. Older combustors usually operate with ratios in the range of 1.9 to 2.5.

The distribution of the air depends on the process control system. In the past the total amount of air was kept constant and only the ratio between primary and secondary air was adjustable. If more heat generation was required (more steam production) more primary air was supplied through the grate and less secondary air. Usually the distribution of the primary air over the grate was fixed.

In the described system, which monitors the heating value of the waste (through the moisture content of the gas phase in the first part of the grate), the air ratio and distribution is adjusted according to the obtained information. A slight increase in heating value (less water, more volatilization in the first part of the grate) means a little increase in primary air supply to that area, to supply enough oxygen. However, if the heating value increases further, this air supply is decreased, to prevent high local temperatures, that might damage the grate and cause high NO_x -formation. Then the secondary air is used to supply the required oxygen and to ensure the burn-out of the gases. Because the primary air is also required for the cooling of the grate, there is a limit to the heating value of the waste that can be incinerated on a grate. With extremely high heating values (13 - 14 MJ/kg), only 30% of the total amount of air is supplied through the grate, the rest is secondary air [8]. Thus the combustion on the grate and the heat load on the grate are lower. If a low amount of primary air is applied, the burn-out of the bottom-ash requires special attention.

To ensure complete burn-out of the volatiles in the first empty pass(es) of the boiler (the 'freeboard'), these need to be mixed with air (oxygen) very thoroughly. This mixing has to be assured by the geometry of the combustion chamber, including the entrance to the freeboard, in combination with the way the secondary air is introduced. If the mixing is not optimal also the residence time is important. Most modern emission guidelines require such a geometry of furnace and boiler that a residence time of the gases of at least two seconds at a temperature level above 800 or 850 °C (at oxygen levels above 6 vol%) is ensured after the last injection of air. This serves as a backup guarantee for complete burn-out if the mixing has not been complete.

2.1.5 Primary flue gas emissions

The emissions of HCl , HF and SO_2 cannot be influenced by the way a combustor is designed or operated: this is determined by the concentration of Cl^- , F^- and S -compounds in the waste. Only if Ca -compounds are added to the waste prior to combustion, a part of the S , Cl^- and F^- is retained in the bottom-ash, reducing the flue gas emissions of these components [9]. However, this decreases the quality of the bottom-ash considerably.

The emission of particulates is only slightly affected by the amount of primary air and the way at which this primary air is blown through the grate and the velocity: higher velocities will cause more particle entrainment.

Emissions of NO_x , CO , unburned hydrocarbons and PCDD/F are determined by a combination of many parameters like geometry, process control, air supply and air

distribution, waste composition and homogeneity. NO_x is of course also partly determined by the N-content of the waste.

Average emission levels that have been demonstrated (no extremes) in modern combustors without further treatment are given in Table 2.

Table 2 Emission levels attainable through primary measures (in the combustion process), in modern combustors (no extremes)

Component		Level	Reference
CO	[mg/m ³ ₀]	10 - 30	2, 15, 17
NO _x	[mg/m ³ ₀]	200 - 350	5, 16, 18
TOC	[mg/m ³ ₀]	< 1	5, 16
PCDD/F	[ng TEQ/m ³ ₀]	1 - 8	19
Burn-out bottom-ash	[wt%-C]	1 - 2	5, 6, 16

From the references it becomes clear that there is no unambiguous effect of the grate type; although differences in performance of various grate systems do occur, it is not possible to prove a significant relation to the specific grate type, as long as it allows for a good air distribution and process control.

Also the furnace geometry (parallel flow, counterflow or intermediate-flow) by itself, does not form a restriction, to reach the levels presented in Table 2.

(Ref. 2, 5, 15 are forward acting grates with counter- or intermediate-flow geometry, ref. 16 is a roller grate with parallel flow, ref. 6 a reverse acting grate with counterflow).

The decision which grate or geometry is to be applied, apparently has to depend on other parameters like durability, waste characteristics, and commercial aspects.

2.2 Fluidised bed incinerators

In a fluidised bed combustor (FBC), the material is incinerated in a fluidised sand bed at a relatively low temperature, usually somewhere between 750 and 900 °C. Characteristic properties of this system are the high thermal inertia, because of the large amount of bed material compared to the amount of waste that is maintained on the desired process temperature, and the very good heat and mass transfer in the bed. This makes the system relatively insensitive to variations in the composition and heating value of the material fed to the combustor. Because the process temperature can be controlled independent of the heating value of the fuel, there is practically no restriction to incinerate waste streams with a high calorific value. The direct result of the specific properties of FBC systems is a very good combustion efficiency of 99%+. Because of the low and homogeneous combustion temperature the NO_x emission is low compared to grate systems, where peak temperatures are higher. This can be further improved by applying not only primary (fluidisation-)air but also secondary air. SO_2 emission and to a certain extent also HCl and HF emissions, can be limited by supplying limestone to the bed. It is relatively easy to stop and start up an FBC unit very fast, by interrupting resp. restoring the fuel and air supply, which is an important advantage in case of intermittent operation.

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Some of the characteristics of the FBC system are less favourable e.g. the additional requirements regarding preparation of the waste to be fed to the combustor. The feed preparation is necessary to remove metals as far as possible, because they might obstruct the bed ash drain system, and to limit the maximum size of the material, (usually < 150 mm) to be able to maintain a proper fluidisation.

An important characteristic of all FBC systems is, that none of the ash residues have passed a high temperature zone, meaning that sintering has not occurred. This means that the FBC ashes will be less inert than bottom-ashes from a grate firing system (higher leachability) and that some ways to re-utilise these ashes are not possible with FBC ashes. In case of limestone injection in the bed, in order to reduce SO_2 emissions, the amount of ash increases significantly.

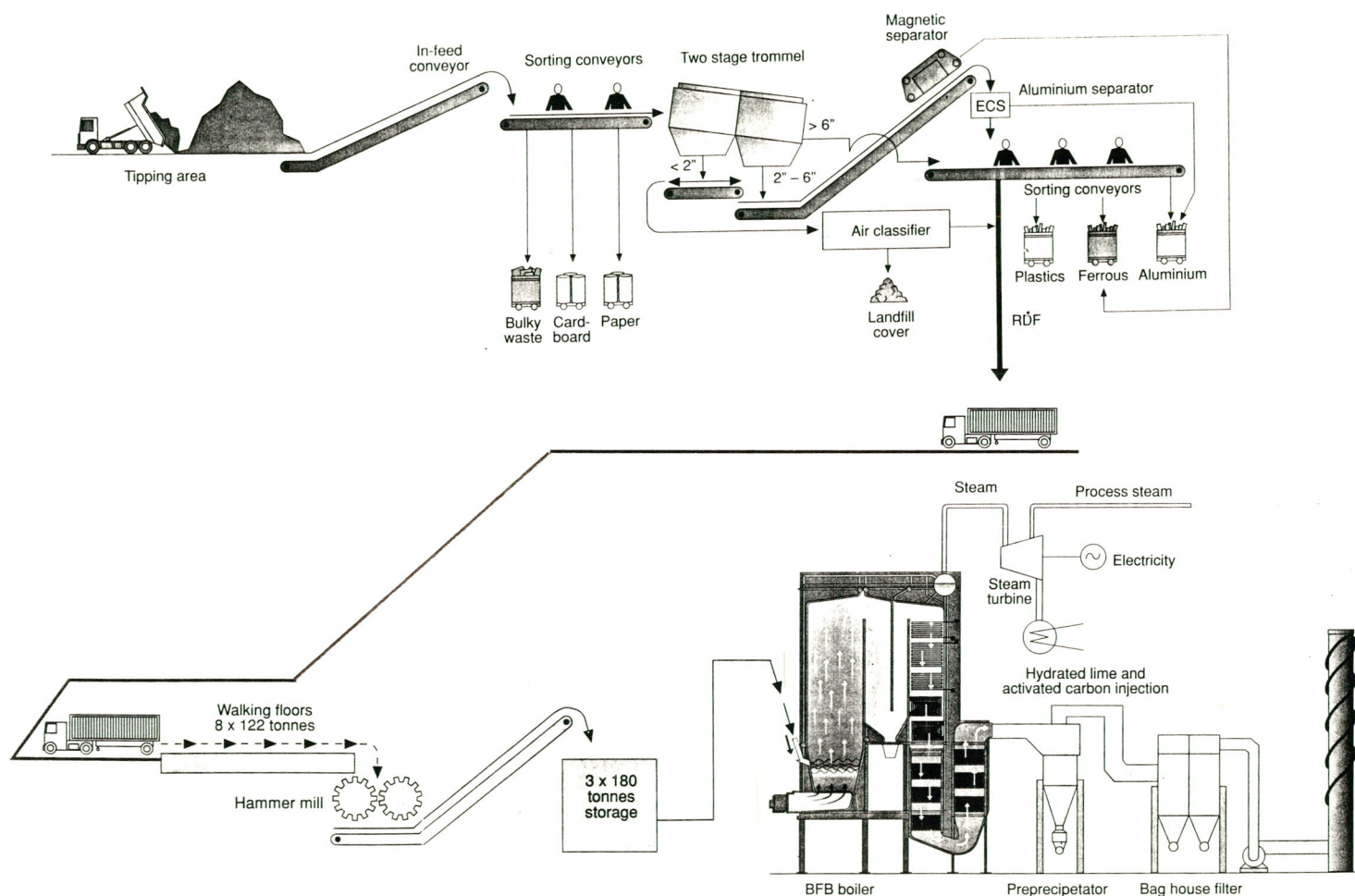


Figure 10 AFBC MSW incineration system (Fayetteville, Kvaerner)

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Different types of FBC systems are applied for MSW incineration.

— AFBC

The most common, shown in Figure 10, is the Atmospheric Fluidised Bed Combustor (also called Bubbling FBC). In this type the fluidisation velocity is rather low (< 3 m/s), meaning that only very fine particles, that are almost completely burnt out, are blown out of the bed and collected in the dust removal system. The largest part of the ash is drained from the bed as bottom-ash. Directed air nozzles may be used to force larger non combustible parts to the bed drain. Screening and recycling of the bed ash is required to remove these parts out of the bed material.

— ICFBC

A special design, the Internally Circulating or Revolving type FBC, has been developed by Ebara (Japan), which allows MSW to be incinerated with minimal pretreatment (Figure 11). This is based on the geometry of the bottom and sidewalls and the primary air distribution in the bed, resulting in a combination of a vertical and a strong horizontal movement in the bed (Figure 12). Around 40 of these units are in operation in Japan; the first in Europe (Berlin, Madrid) are under construction.

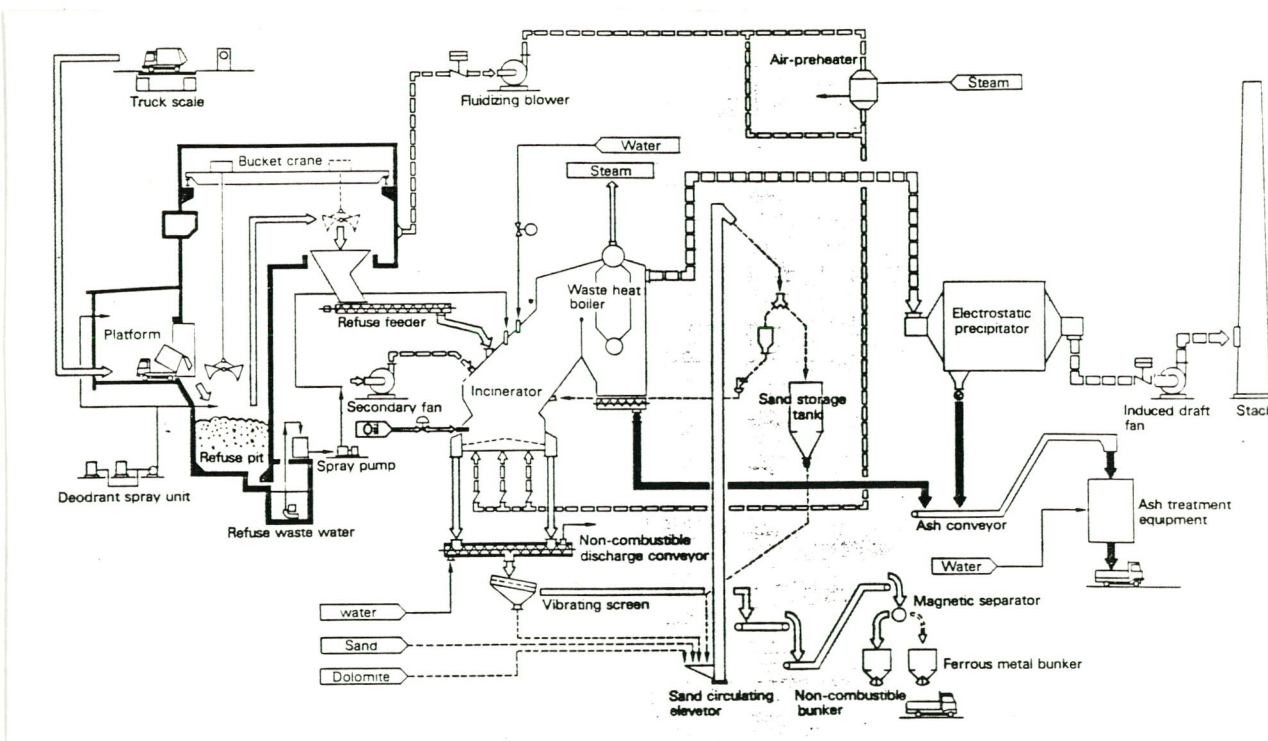


Figure 11 Ebara MSW incineration system

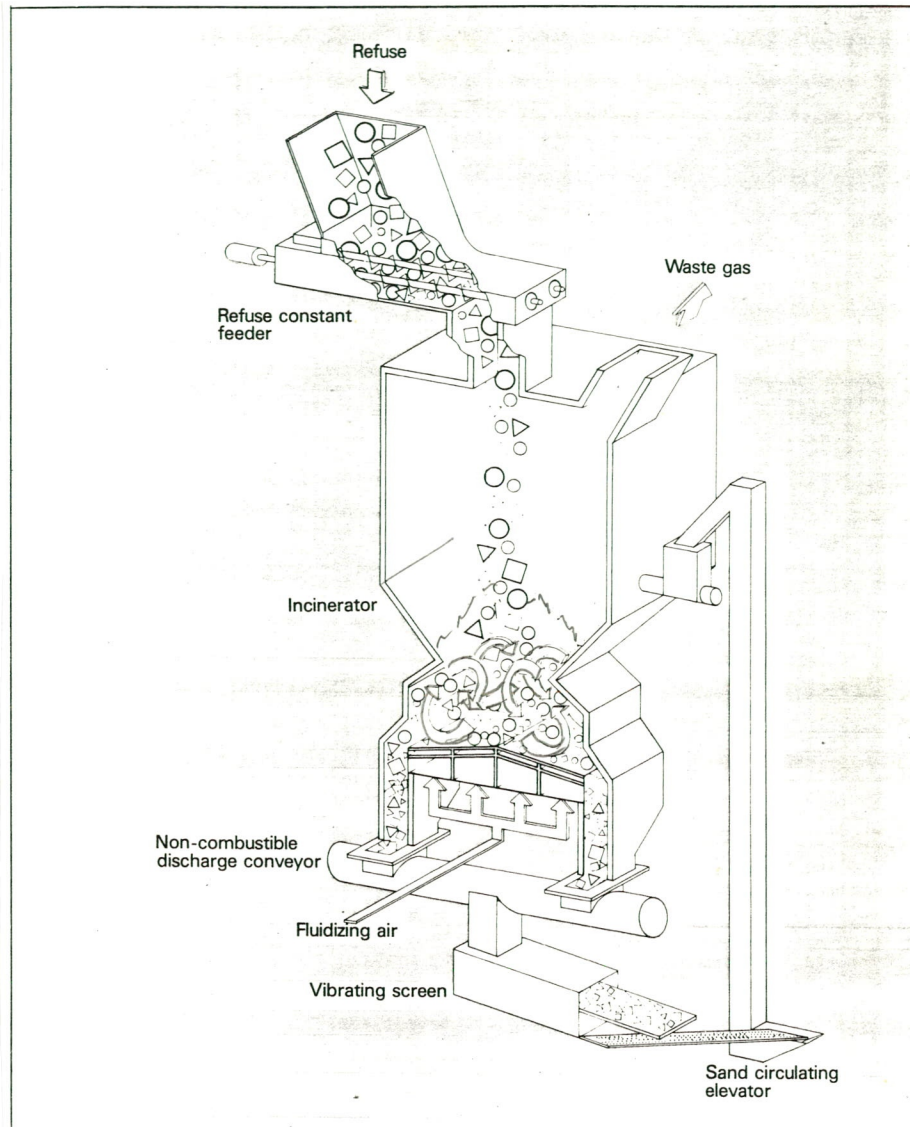


Figure 12 Ebara revolving type fluid bed incinerator

— CFBC

The Circulating Fluidised Bed Combustor (CFBC, Figure 13) is a common system for the combustion of coal and also for some waste materials like wood waste and RDF. It is more critical as far as the size of the fuel is concerned, because the material is circulated inside the system by applying a higher fluidisation velocity (around 6 m/s). The advantage over the bubbling type is that less feed points are required. Wear by erosion however is high in the main combustion area, so heat transfer to the boiler tubes has to be located in a different area. The emissions of NO_x and CO are somewhat lower. At present there are no

installations in operation on MSW only, although at least one manufacturer (Kvaerner) offers this system commercially.

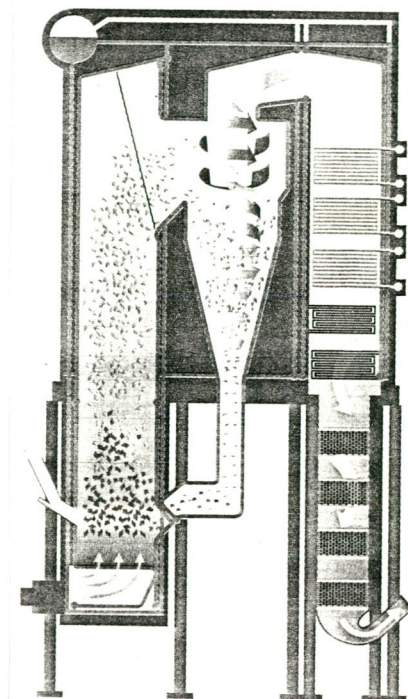


Figure 13 Circulating fluidized bed incinerator (Kvaerner)

Although the primary emission data of FBC systems compare favourably to these of grate systems, this does not imply that all current stringent emission standards can be met without additional measures.

As an example, without pretending that these data are representative for FBC installations, Table 3 presents emission data that are claimed to be realised in a 2 * 11 ton/h FBC incinerator under construction in Fayetteville (USA) by Kvaerner. This installation will process shredded RDF, produced from MSW in a Material Recycling Facility (MRF) where it is subsequently hand sorted (removing bulky waste, paper and cardboard), sieved (removal of fines), magnetically and Eddy Current separated (removal of ferrous material and aluminium), and finally hand sorted once more (removal of plastics). Apart from limestone addition to the bed and the baghouse filter the following emission reduction measures have been taken:

- Thermal NO_x reduction

- HCl removal by hydrated lime injection

- Hg and dioxin reduction by activated carbon injection in the fluegas duct

Table 3 Envisaged emission data from the Fayetteville FBC

Component	Emission, mg/m ³ ₀ (dry gas, 11% O ₂)
NO _x	75
SO ₂	59
CO	75
Hg	0.05
HCl	97% reduction
PCDD/F (total)	21 ng/m ³ ₀ ¹⁾

¹⁾ This corresponds to approx. 0.2 ng TEQ/m³.

2.3 Other systems

A few other systems, basically different from the two types described above are applied in the MSW incineration field. These all have or had specific advantages in the situation in which they are applied, usually on a relatively small scale. Because application on a larger scale in the near future is unlikely, only a short description is given.

Modular incineration systems

Modular incinerators are pre-fabricated 'standard' units, resulting in relatively low investment costs. The capacity, is in the range of 10 - 100 tons/day. Untreated MSW is incinerated in a two stage combustion process (Figure 14). The primary chamber is either used as a sub-stoichiometric (starved air system) or as a over-stoichiometric unit (excess air incinerator). In the secondary chamber the combustion process is completed. The waste stream is moved through the primary chamber by transport rams. Air is supplied through ports in the walls.

Favourable properties of the modular incinerator are the low investment costs and the relatively low particulates emissions, particularly in case of the starved air system that features low air velocities in the primary chamber. On the other hand the burn-out is lower (unburnt carbon > 6%) and the energy recovery efficiency is also lower than in the moving grate systems described above. Also the throughput per unit is lower than for moving grate installations. A typical application is the incineration of hospital waste.

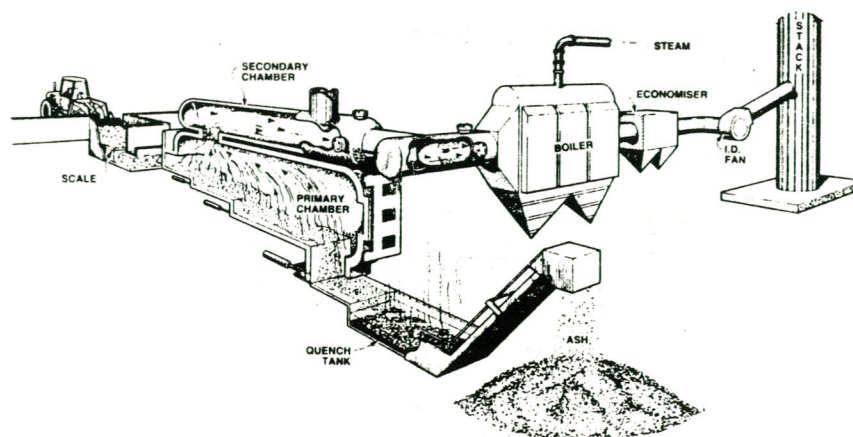


Figure 14 Two stage modular incinerator

Rotary/Swinging Kiln

These two systems, developed by Westinghouse/O'Connor (WOC) resp. Laurent Bouillet Ingenierie (LBI) both have a certain similarity to a 'conventional' rotary kiln. In both cases the installations are intended for small scale applications (LBI: 3 - 10 ton/h [10]). They consist of conically shaped kilns. The LBI swinging kiln does not rotate 360 degrees, but approx. 100 degrees to both directions (Figure 15), thereby mixing and transporting the waste. Primary air is supplied through holes in the lower half. The WOC incinerator rotates completely and has a perforated water-cooled metal wall, through which combustion air is supplied from the bottom section.

Both systems provide a very good air distribution and mixing, resulting in a high combustion efficiency.

The lower throughput and higher maintenance costs limit their application.

Characteristic performance data of the swinging kiln are [10]:

- CO 20 - 50 ppm;
- $C_xH_y < 10$ ppm;
- O_2 at exit 7 - 10%;
- NO_x 120 - 200 ppm;
- unburnt 1 - 1.5%;
- PCDD/F 0.3 - 0.7 ng TEQ/m³₀ (EPA equivalents).

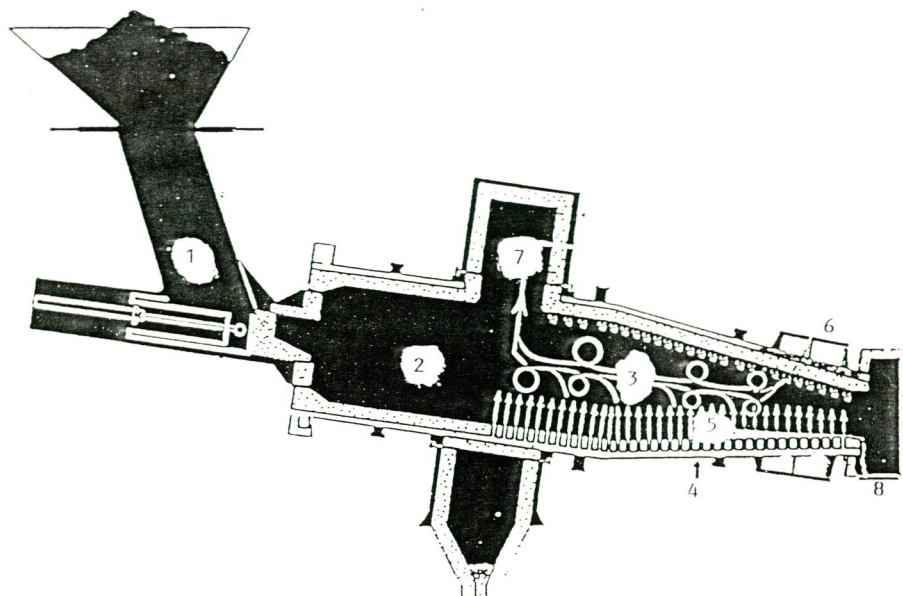


Figure 15 LBI Swinging kiln

Vølund system

The Vølund system is a combination of a grate and rotary kiln incinerator (Figure 16). The drying and devolatilization takes place on the grate that forms the first part of the system, combustion of the solids is completed in the rotary kiln. The high investment cost of this type of installation, specially for a high capacity system is apparently a major drawback.

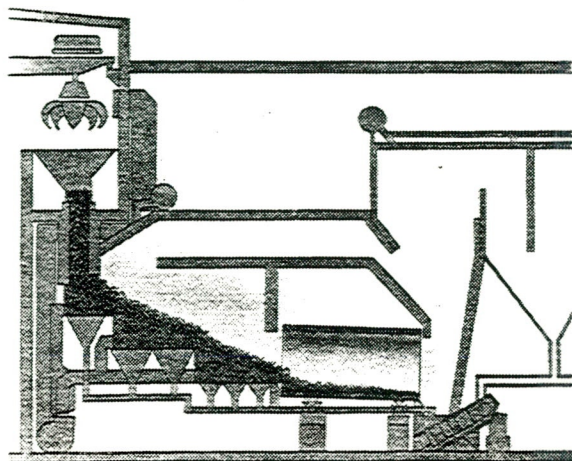


Figure 16 Vølund incinerator

3 Boiler

A further objective of MSW combustion is to recover energy from the waste.

There are different ways to recover the energy from the flue gases (steam, hot water, direct drying). The most flexible way is to produce steam which is used for electricity generation, with or without utilisation of the remaining low temperature waste heat.

In case of steam production the superheated steam is fed to a steamturbine-generator which generates electricity. The low pressure steam leaving the turbine still contains energy which can be used for district or process heating. The total energy recovery efficiency to electricity is limited to around 22% at the 'standard' steam conditions (temperature 400 °C, pressure 40 bar). In case there is sufficient heat demand a combined heat and power installation is feasible, allowing efficiencies up to 60%.

3.1 Horizontal versus vertical

In principle there are two types of steam boilers which are used for the energy recovery from waste: the vertical boiler and the horizontal boiler. Hereby the terms horizontal and vertical relate to the flow direction of the flue gases in the convective part of the boiler (Figure 17).

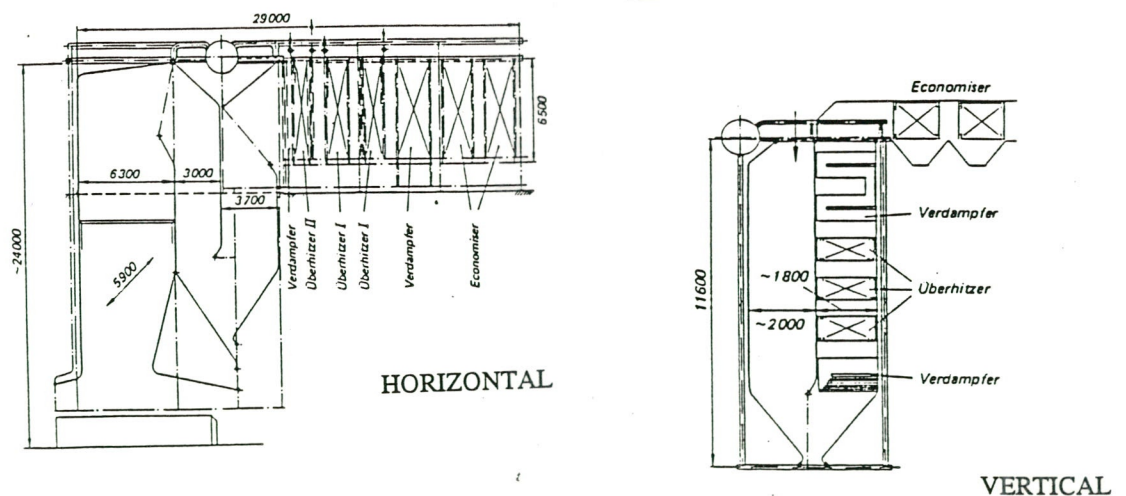


Figure 17 Horizontal and vertical boiler design

The first part is the same for both type of boilers. In this part heat is transferred by radiation which means that there are no tubes in the gas stream but only in the walls (empty drafts). In the beginning of the radiation part these membrane walls are shielded to make sure the temperature does not drop too much, because as already mentioned the flue gases need a residence time of at least 2 seconds at temperatures above 850 °C.

Depending on the size of the boiler and the velocity of the flue gases, the boiler is equipped with one, two or three empty drafts. In these empty drafts the flue gases are cooled to 600 - 700 °C before entering the convective part [11].

In the convective part the flue gases are generally cooled to 200 - 250 °C before leaving the boiler.

Fly-ashes and other particulate matter from the flue gas tend to build up on the surface of the convective tubes, causing a decrease in heat transfer and a possible increase in corrosion (see paragraph 3.2).

In the horizontal boiler the tubes are hanging vertically and can easily be cleaned by installations which knock against the tubes. This can be executed continuously if necessary. By the vibrations caused by this knocking, particles clinging to the tubes will fall off. In vertical boilers, where the tubes are placed horizontally, knocking is not very effective. Furthermore the dust that falls off, will very likely land on a tube below the one it came from. It will thus take a very long time before the particles are removed from the flue gas stream. Therefore in vertical boilers the main cleaning method is soot-blowing, usually with steam. Through several blowers once or twice a day steam is blown between the tubes to remove the dust on the tubes. The costs related to the use of steam is a major disadvantage of this system. Furthermore the flue gas cleaning system has to cope with peak concentrations of dust together with the temporarily high flue gas stream (flue gas + steam). Finally the soot-blowers have to be oriented very carefully to make sure that no damage to the tubes occurs by erosion.

Regarding investment costs and space occupation the vertical boiler is preferable.

Both boiler types are known to reach uninterrupted operating times of 8000 hours at availabilities of 80 - 85% and there are no really decisive technical and operational differences between the two. Often the selection has to be based on specific local demands like the availability of space or height, especially in case of extensions or retrofits of existing installations. When these demands are not present the horizontal boiler is more often applied than the vertical one.

3.2 Steam parameters, corrosion and erosion

The efficiency of the heat recovery increases when the steam parameters (temperature and pressure) increase. In normal power plants (fossil fuel fired) generally up to 550 °C and 225 bar are applied for steam [12]. In MSW combustors these parameters usually are kept far below that level because of corrosion problems. Due to CO, HCl, particulate matter (metal salts) and alkylsulphates, corrosion of the tubes is very quick above surface temperatures of 400 - 450 °C [12, 13, 14]. Below these temperatures the main cause of corrosion is CO in combination with HCl. By oxidation of the tube material, a protective layer of metal-oxides is formed; if CO is present, it reduces these oxides after which Cl⁻ corrosion of the metal takes place rapidly. The two main concerns to prevent corrosion thus are keeping the tube

surface temperature close to or below 400 °C and ensuring a good burn-out of the volatiles (low CO).

The first of these concerns is handled in several ways:

- Where the temperature in the boiler is too high the tubes are shielded with a protective (ceramic) material: this is mainly the case in the first (radiative) part of the boiler.
- The convective part is designed so that in the first bundle of tubes water is evaporated. This causes a quick drop in the gas temperature and because water is evaporated in the tubes, the surface temperature remains relatively low. This first bundle also causes swirls, providing additional mixing, to promote contact and reaction between CO and unburnt particles and oxygen [11].
- The superheater tubes are placed co-current to the flue gas stream because this keeps the tube surface temperature lower than in counter-current flow [11].

The second concern, low CO, is first of all realised through good combustion practices as described in chapter 2.

A lot of wear and corrosion is caused by fly-ash. At high temperatures (> 700 °C) fly-ash weakens and gets sticky. If it encounters surfaces, a build-up of material will take place, decreasing the heat transfer. After a while this build-up will get so heavy, that it will fall off again, taking with it parts of the protective layer and damaging the part it lands on (usually the grate). Besides that, the fly-ash can also through reaction with the protective layer weaken this material (spalling, cracking), causing it to break up. When the fly-ash contains unburnt combustible matter (which it normally does: 1 - 5 wt%) it can produce CO which, as described, can cause corrosion.

At low flue gas temperatures, dew point corrosion can take place. Normally this does not cause problems if the tube surface temperature is kept above 180 °C.

Besides corrosion also erosion can take place, especially if soot-blowing is applied without the proper care.

In general, boilers in MSW combustors are designed with steam parameters of 40 - 45 bar and 400 - 450 °C [11, 13]. Despite corrosion, which always takes place, uninterrupted operation times of over 8000 hours are guaranteed. An impression of the relation between service lifetime and steam temperature is given by Figure 18. This figure is based on operational data from a large number of German combustors [13].

By choosing higher temperature resistant (but also more expensive) tube material it is possible to go up to steam temperatures of 500 °C. Limited practical experience is available in Germany.

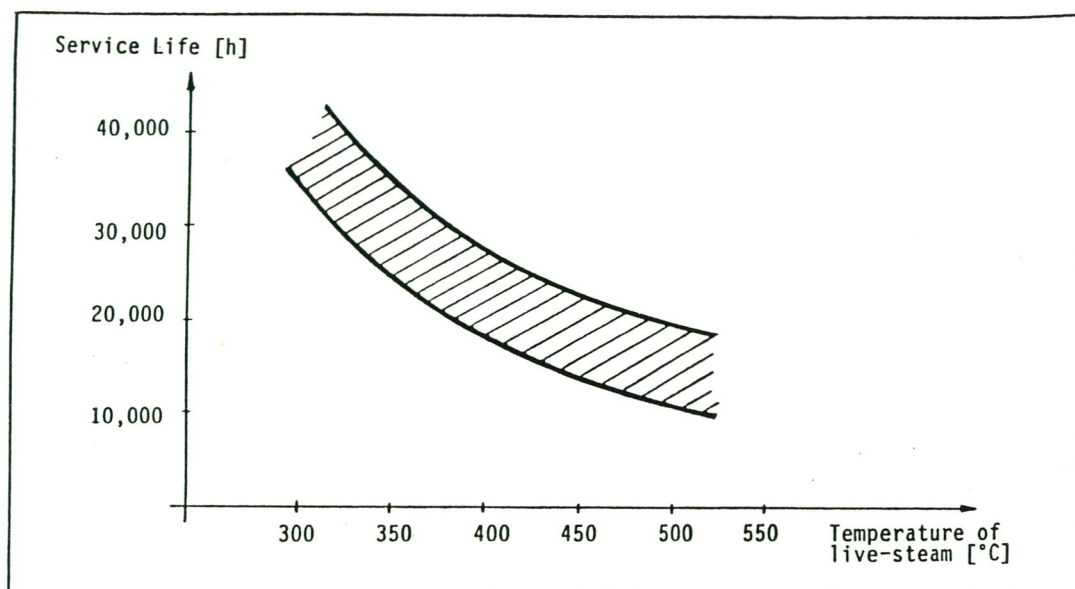


Figure 18 Lifetime versus steam temperature

4 Flue gas cleaning system

When the flue gases leave the boiler, the concentration of pollutants can differ over a wide range depending on combustor feed composition and combustion practice. A typical composition of untreated fluegases for a modern combustor is given in Table 4.

As a reference the Dutch emission standards are given and the required removal efficiency.

Table 4 Typical composition of raw flue gas (before cleaning) [2, 5, 6, 15, 16, 17, 18, 19]
(All values in mg/m³₀ dry gas and 11 vol% O₂)

Component	Raw flue gas concentration		Dutch standard	Removal ¹⁾ efficiency [%]
	minimum	maximum		
Dust	2000	5000	5	99.9
HCl	800	3000	10	99.7
HF	10	100	1	99.0
SO _x (as SO ₂)	200	1500	40	97.3
NO _x (as NO ₂)	200	500	70	86
CO	10	50	50	-
TOC (as C)	1	20	10	-
Heavy metals:	0.1	1	0.05	95
Hg	0.1	0.5	0.05	90
Cd	1	5	1	80
others				
PCDD/F [ng TEQ/m ³ ₀]	1	10	0.1	99

¹⁾ With the exception of CO and TOC (Total Organic Carbon) all components are reduced in a modern flue gas cleaning system.

In this chapter the required flue gas cleaning equipment is discussed per group of pollutants which needs to be removed from the flue gases. These groups are: particulates/dust (4.1), acid gases (4.2), NO_x (4.3), dioxins and furans (4.4) and heavy metals (4.5).

4.1 Particulates/dust

Almost always the first step in a flue gas cleaning system is removal of particulates. This is done for two reasons. First of all, dust has a negative influence on the functioning of the other flue gas cleaning equipment. Secondly, the possibilities for reuse of fly-ash are better if the fly-ash is separated before scrubbing.

For this there are two reasons:

- the fly-ash does not contain additives (used in the semi-dry or dry scrubber);
- the heavy metal content is lower, because the fly-ash is collected at higher temperatures, and a lot of heavy metals have not condensed yet. (After the scrubber the temperature is much lower).

To remove the fly-ashes from the flue gases several techniques can be used.

— ESP

A common technique is the use of an electrostatic precipitator (ESP), capable of reaching removal efficiencies of 95 - 99%, depending on the number of electric fields that is used. Particles smaller than 2 μm are less efficiently caught [18].

Of special interest is the temperature at which the ESP is operating and the residence time of the flue gases in the ESP, considering the formation of PCDD/F (De-novo-synthesis [20, 21, 22, 23, 24]). For this reason the temperature should be kept at 180 - 220 °C.

— Fabric filter

An even better removal efficiency (> 99.9%) can be realised by using a fabric filter (= bag filter or bag house). This system however, is relatively expensive and causes a relatively large pressure drop. It also needs a maximum temperature protection, usually the temperature has to be below 180 - 200 °C, but above the dew point of the gases. Because of its high removal efficiency and the need to remove as much fly-ash as possible before further cleaning, fabric filters are applied more and more.

Together with the dust some more components are removed, like heavy metals and PCDD/F (see paragraph 4.4). This is strongly dependent on the temperature of the flue gas (condensation of gaseous heavy metal compounds) at which the dust is removed.

Remaining particulates will be caught in the installed downstream equipment (scrubber, active cokes filter).

4.2 Acid gases

For the removal of acid gases (HCl, HF, SO_x), in principle three different techniques can be applied: dry scrubbing, semi-dry scrubbing and wet scrubbing. All these systems use an ad- or absorbent which is sprayed in the flue gas stream.

Dry scrubber

The dry technique uses a dry additive to adsorb the acid gases, usually calcium hydroxide powder with a large specific surface area, sometimes in a mixture with active cokes. The scrubber is always followed by an ESP or a fabric filter to remove the solids (with the adsorbed acids) from the gas stream. A fabric filter has an advantage over an ESP because of the higher removal efficiency and also because on the filter, a layer of the adsorbent builds up, acting as a fixed bed adsorber, greatly improving the effect. To increase the removal efficiency, the flue gas is cooled by water injection (to 140 - 180 °C) before entering the scrubber. The quenching causes

condensation of most of the heavy metals (except Hg and to a lesser extent Cd and Tl) and subsequent separation in the ESP or fabric filter.

The major disadvantage of this dry system is the considerable amount of adsorbent which is needed. Due to the nature of the adsorption process (adsorption of gases to solids) a stoichiometric ratio of 1.8 to 3.5 (average 2.5) [25, 26] is required to adsorb enough acid gases to comply with the regulations. This not only means high costs for the use of relatively large amounts of adsorbent, but also the amount of residues is relatively large: 25 - 45 kg residue per ton MSW combusted [25, 27, 28]. So far there are no possibilities for reuse or recycling of these residues, which means they have to be landfilled, usually as hazardous waste (high costs).

A dry scrubber is easy to operate and requires relatively small investments.

Besides removing acid gases the dry scrubbing technique is capable of removing part of the remaining dust, heavy metals and PCDD/F, especially when active cokes is mixed with the lime [29]. Without special measures and large supply of adsorbent this will, however, not be enough to reach emission levels required by the regulations in Germany, Austria or the Netherlands.

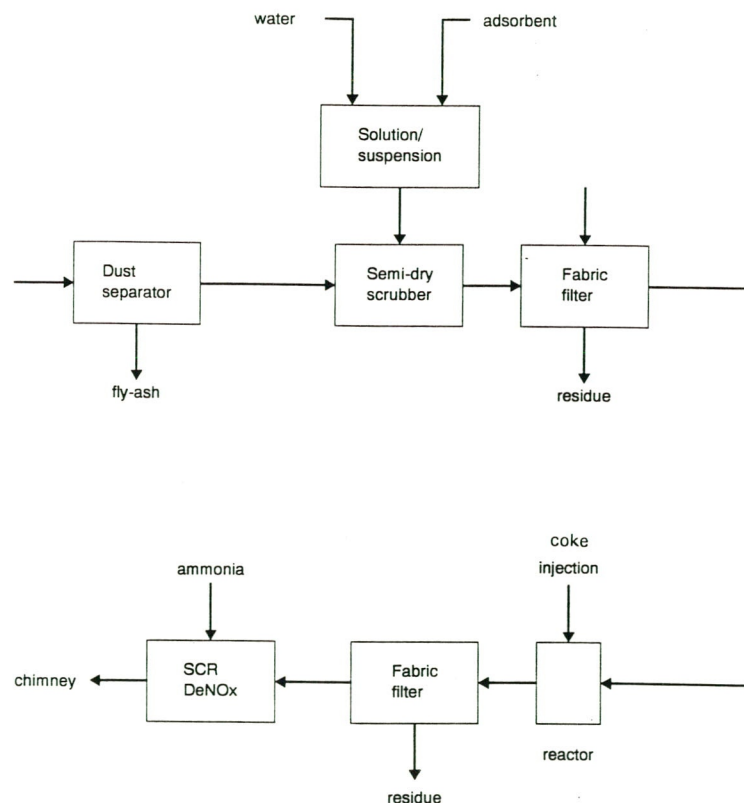


Figure 19 Schematic diagram of semi-dry scrubber unit

Semi-dry scrubber

In a semi-dry scrubber a solution or suspension of lime (and active carbon) in water is sprayed. The solution absorbs the acid gases, the water of the injected solution/suspension evaporates (thus cooling the flue gas) and the residue is removed from the flue gas as a solid in the subsequent ESP or fabric filter.

Figure 19 shows the block scheme for a semi-dry scrubber.

Due to the use of an absorbent in liquid form, the required stoichiometric ratio can be much lower compared to dry scrubbing: 1.2 - 2.5 (average 1.8) [25, 26], so the costs of the adsorbent are less. Evidently also the resulting amount of residue is less [25, 27, 28]. Like the residue from dry scrubbing, the residue from semi-dry scrubbing cannot be reused or recycled and has to be landfilled as hazardous waste. In the same way as in the dry scrubber, part of the remaining dust, heavy metals and PCDD/F is captured in the semi-dry scrubber. The removal efficiency is better than that of the dry scrubber and in some cases, if active cokes is injected simultaneously, the most severe regulations can be met [30, 31].

However, operation is slightly more difficult and the investments are slightly higher for semi-dry scrubbing in comparison to dry scrubbing.

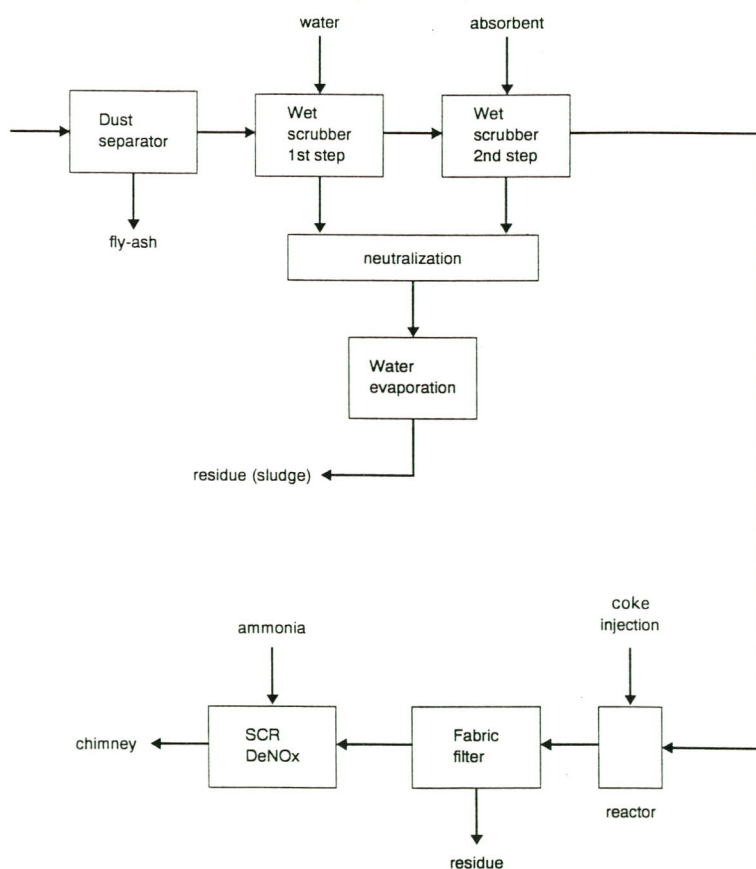


Figure 20 Schematic diagram of two stage wet scrubber

Wet scrubber

Wet scrubbers also use a liquid absorbent, but contrary to the other two systems, the residue also is a (waste) liquid. Modern wet cleaning systems are multi-staged: the first is an acid stage and the second a basic or neutral stage.

In the acid stage, water is sprayed in the flue gas, absorbing HCl, remaining dust and condensed heavy metals. The washing water of this stage is recycled over the scrubber and because of the absorbed HCl the pH drops to 0.5 - 1. This favours the absorption of especially Hg.

SO₂ is not very well absorbed in an acidic environment and therefore in the second stage the pH is adjusted to 7 or higher by spraying sodium- or calciumhydroxide solution in the scrubber.

Figure 20 shows the block scheme of a wet scrubber.

Because of the good contact between flue gas and wash fluid, the required stoichiometric ratio is almost 1 (1.0 - 1.1) [25]. The resulting waste water can be treated, cleaned and disposed of, or it can be neutralised and evaporated. This evaporation can take place separate from the flue gas cleaning system or integrated in a spray dryer (Figure 21). The resulting solid residue amounts to 10 - 15 kg per ton of MSW combusted [25, 27]. Like the residue from dry and semi-dry scrubbing the residue from evaporation of washing water cannot be reused or recycled and has to be landfilled as hazardous waste. However, more and more permits require avoidance of any waste water discharge if a wet scrubber is used.

The wet cleaning system not only has the lowest amount of residues, it also has the highest removal efficiency for acids, dust and heavy metals. A large fraction of the Hg in the flue gas stream remains in the gas phase and is difficult to capture. Therefore sometimes additives such as TMT15 (mercaptan) are added to the second stage of the scrubber, resulting in higher absorption of Hg [16].

PCDD/F is not captured in a wet scrubber, except for the PCDD/F which is adsorbed to particles or droplets. Practical experiments with the addition of active cokes to the washing water of a wet scrubber are being carried out to test the increases of the absorption of Hg and PCDD/F.

The wet scrubber needs very careful operation and requires higher investments in comparison to the dry and semi-dry scrubber.

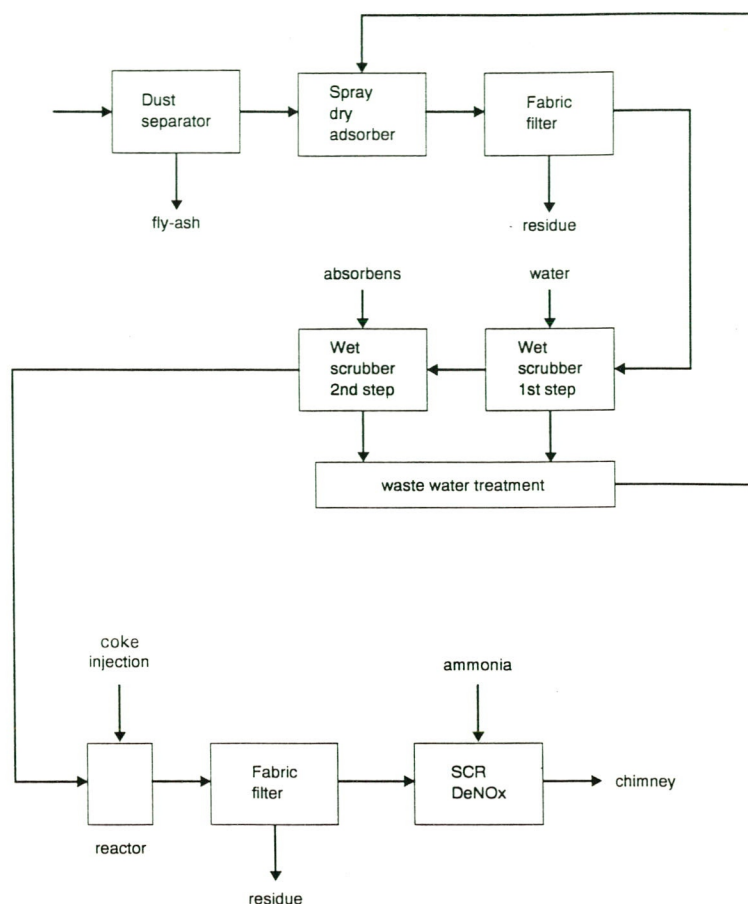


Figure 21 Schematic diagram of spray dryer

4.3 NO_x

The NO_x -emission can be controlled by primary and secondary measures.

Primary measures.

To minimise the formation of NO_x out of fuel-bound or atmospheric nitrogen, measures can be taken in the combustion chamber as described in chapter 2. The two main methods, of which the first is the most important, are the following:

- Optimize the amount of excess air (oxygen), especially in the hottest parts of the combustion chamber, to minimise the formation of NO_x out of fuel-bound nitrogen (air and fuel staging [17]). This is achieved by dividing of combustion air in primary and secondary air in a carefully controlled way and by using recycled flue gases as (part of the) secondary air.
- Prevent the formation of thermal- NO_x (from reaction of atmospheric nitrogen with oxygen) by keeping the temperature below approx. 1200 °C, not just average,

but also locally (prevent hot spots). This is done by creating proper mixing, which has to be achieved by proper design of combustion chamber and furnace.

With these primary measures, NO_x -concentrations of 250 - 350 mg/m^3_0 in uncleaned flue gas can be reached (table 4).

In case emission regulations require the NO_x -emission to be reduced to 200 or even 70 mg/m^3_0 , additional secondary measures are needed.

Secondary measures.

In principle there are three processes which can be applied for reducing the NO_x -emission:

- SNCR: Selective Non-Catalytic Reduction;
- SCR: Selective Catalytic Reduction;
- Adsorption and catalytic reaction on active cokes (see section 4.4.1).

Besides these technologies, also chemical adsorption with sodiumperchloride (not successful yet [16]) or reaction with hydrogenperoxide (pilot-plant scale) seem to be theoretically possible.

SNCR

A solution of ammonia or an ammonia-forming compound (e.g. urea) is sprayed in the flue gases in the furnace. At temperatures of 900 - 1050 °C the ammonia reacts with NO_x to N_2 and water [32]. The location of the injection points, usually installed at two or three levels, is very critical, because the temperature range in which the reaction runs properly, is very narrow. Usually a ratio (NH_3 over NO_x) of 2 - 4 is applied, resulting in some ammonia slip, which has to be caught by wet scrubbing, followed by stripping of the waste water and recycling of the NH_3 [33]. At these ratios NO_x -emission reductions of 60 - 80% are claimed to be possible with SNCR [18, 25].

The investment costs of SNCR are low. The major disadvantage is the ammonia-slip which requires removing equipment and decreases the quality of the fly-ash. Furthermore, in the presence of SO_3 and Cl^- , NH_3 can form highly corrosive ammoniumsulfate and ammoniumchloride [33]. Emission levels of 70 mg/m^3_0 (with acceptable ammonia-slip) are hardly reached with SNCR [34].

SCR

With an SCR-De NO_x process the same reactions occur as with SNCR. By using a catalyst (mainly V_2O_5 , WO_3 on a ceramic support material), the temperature range at which these reactions occur is much lower (200 - 300 °C). In the flue gas cleaning sequence there are several places where the SCR could be located, in MSW combustion it is usually situated after the scrubbers. This is to prevent the catalyst from being poisoned with particulates and heavy metals.

The SCR-process uses a near stoichiometric amount of ammonia, causing very low ammonia emissions (< 5 ppm by volume is possible [34]). A NO_x -emission reduction of 90% can be reached [25]. Disadvantages are the investment and operational costs

caused by the use of a catalyst, with a recorded lifetime over 3 - 5 years, and the need to heat up the flue gases to the desired reaction temperatures.

An additional advantage of the SCR technology is the possibility to combine the reduction of NO_x with a reduction of the PCDD/F-emission, by installing a larger catalyst surface (see chapter 4.4).

4.4 Dioxins and furans

For the emission reduction of PCDD/F, several techniques are applied or investigated. First of all there are primary measures, like improved process control (destruction of organic matter: precursors for PCDD/F), temperature and residence time control of the flue gases (to avoid the temperature window where de-novo-synthesis takes place [20, 21, 22, 23, 24]) and high temperature dust removal (removing the particles acting as a catalyst for the de-novo-synthesis). Although it is not exactly clear which lower limit can be reached by these methods, at present additional measures are required to comply with the most stringent standards, allowing 0,1 ng TEQ/m³.

Secondary measures are applied to remove PCDD/F once these have been formed:

- adsorption on active cokes;
- catalytic oxidation (in combination with SCR).

4.4.1 Adsorption on active cokes

For the adsorption of PCDD/F on active cokes several methods are applied. The first, which is the easiest and the least expensive, is the injection of coke particles together with calcium hydroxide in the flue gas stream (EFR: entrained flow reactor) just before a fabric filter, or together with the other ad- or absorbent in a dry or semi-dry scrubber. As already mentioned, at present experiments are going on with the addition of active cokes to the washing liquid of a wet scrubber.

Secondly, instead of simply injecting the cokes in the flue gas stream, a circulating fluidised bed reactor can be used. In this reactor the cokes is fluidized by the flue gas. The cokes that is elutriated with the flue gas stream, is separated in a fabric filter and recycled to the circulating fluid bed, keeping the consumption of active cokes very low.

The third and widely used technique, in which adsorption to active cokes can be realised, is a cross flow fixed or moving bed reactor containing cokes. Continuously small amounts of contaminated cokes are withdrawn from the bottom and fresh cokes is added at the top. This technique is the most expensive of the three mentioned, but also has the highest removal efficiency. Active cokes filters operate at temperatures below 150 °C to avoid hot spots, excessive CO-formation or even a complete burn-down of the installation.

The main advantage of the active cokes technology is the ability to capture very efficiently almost every pollutant: not only PCDD/F but also other hydrocarbons (e.g. PCB's, etc.), particulates, heavy metals (including the volatile ones like Hg) and acid gases and, with less efficiency, NO_x . The active cokes technology therefore is very well suited to serve as a final security stage.

The use of active cokes for reduction of the NO_x -emission is relatively new. In principle the process is comparable with the SCR-technique with a different catalyst and a different temperature range. This process also uses a near-stoichiometric amount of ammonia, but so far only reaches NO_x -emission reductions of around 60% [25], which might not be enough to reach a limit of 70 mg/m^3 .

The investment costs for all three methods of adsorption on active cokes are considerable and the management of the contaminated cokes residue is difficult (see section 5.4).

In table 5 a comparison is made between the different active cokes techniques.

Table 5 Comparison between three different flue gas cleaning techniques based on adsorption to active cokes [25]

Parameter	Fixed bed	Entrained flow plus bag filter	Circulating fluid bed
Investment costs [%]	100	55	66
Cokes consumption [kg/ton waste combusted]	2.4 - 3.6	1.2 - 1.8	0.3 - 0.7
Pressure drop [mbar]	70	25	40
Removal efficiency acid gases (HCl, HF, SO_2)	high	intermediate	intermediate/high

The use of active cokes requires special attention because of possible CO-formation or self-ignition of the cokes. In the EFR and in the circulating fluid bed, a mixture of cokes and calciumhydroxide (30/70 wt%) can be used, which decreases the risks of self-ignition.

The amount of cokes which is used can have a large impact on the decision which system to apply. This is caused by the fact that the disposal of the used cokes (and destruction of the adsorbed pollutants) is problematic and causes high costs (see section 5.4).

4.4.2 Catalytic oxidation

Instead of adsorbing PCDD/F on cokes, these can be destroyed by catalytic oxidation. It appears that the same catalyst which causes the reduction of NO_x also causes oxidation of PCDD/F to CO_2 , HCl and water. Also NH_3 is oxidized to N_2 and water [25, 34]. This means that if a catalyst with a sufficiently large capacity is installed, more NH_3 can be supplied without an increase of NH_3 slip, realising higher NO_x -emission reductions. Thus, in the last part of the catalyst, where all NH_3 has been oxidised, PCDD/F will be destroyed. Besides PCDD/F also unburnt hydrocarbons (TOC) and CO are oxidised [35, 36].

4.5 Heavy metals

For heavy metals no separate flue gas cleaning equipment is used. Most of the heavy metals are collected with dust (fly-ash) in ESP, fabric filter or wet scrubber. However, some metals (mainly Hg, but also Cd and Tl) remain to some extent in the gas phase, even when the flue gas is cooled below 100 °C [37]. By using additives such as TMT15 in the second stage of the wet scrubber, or by using active cokes adsorption, the concentration of these metals in the flue gas can be reduced below the required emission limits.

5 Residue treatment

As stated before the main objective of waste combustion is to dispose of the waste safely with an acceptable emission level of pollutants and with the highest volume reduction.

In the waste combustion process, several waste streams have to be discharged. First of all the flue gas stream which has been discussed in the foregoing sections. In general, per ton of MSW combusted, 5000 - 5500 m³ of flue gas are generated [37, 38].

Besides flue gas, several solid and liquid residue streams usually leave the MSW combustor:

- bottom-ash from the combustion chamber;
- waste water from the bottom-ash collector;
- fly-ash from boiler and dust collector;
- cleaning residues from dry or semi-dry scrubbers;
- waste water from the wet scrubber or a solid residue after evaporation of the water;
- contaminated active cokes.

In the next sections each residue stream will be discussed.

5.1 Bottom-ash

MSW combustion usually results in 250 - 350 kg bottom-ash per ton MSW combusted [27, 28, 37, 39].

The bottom-ash drops from the grate into a reservoir where the bottom-ash is quenched, consuming around 0.35 m³ of water per ton of MSW combusted [37]. After this stage, usually the bottom-ash is crushed and by magnetic separation the iron is removed. Depending on the applicable standards, often the remaining bottom-ash is reused in construction materials for roads and buildings.

To allow for utilisation in construction materials (or lately even for normal landfill as non-toxic waste in some countries), there are several requirements concerning the composition, which differ considerably between various countries. Mainly the content of unburnt material and of water-solubles is restricted, often also the chemical composition and the leaching behaviour are criteria. Lately these demands have become more and more stringent, requiring either more elaborate treatment of the bottom-ash, improved combustion techniques or even a limited waste acceptance policy.

Treatment

By washing the bottom-ash the water soluble parts can be removed. Sometimes, for this the acidic and alkaline washing water of the wet scrubber is used (MR-process [40]).

Melting does not remove the solubles, but transforms the bottom-ash into a glass-like material, which cannot be leached out any more. This process also produces a heavy-metal-rich residue which might be reused in industry (an example is the Deglor-process [41]; similar processes are developed/under development by Babcock [42]

and Lurgi [43]). Disadvantages of these processes are the relatively high investment and energy costs. Above this, there still are some unsolved technical problems like CO-formation above the melt (explosion risk) and corrosion and low durability of the melting electrodes, which obstruct large scale application of this technique even today.

The costs of disposal of the bottom-ash may have a large impact on the economics of an MSW combustor due to the amount of bottom-ash produced. Therefore a lot of research focuses on more integrated processes, to increase or ensure the bottom-ash quality, thus allowing better (cheaper) reuse of the bottom-ash.

The bottom-ash-quenching water (with high pH) can be used for neutralisation of the waste water from the acid step of the scrubber, or it can be used as washing water in the second step of the scrubber. Normally, however, it is cleaned in a waste water treatment system, together with the wastewater from the wet scrubbers.

5.2 Fly-ash

Per ton of MSW combusted, around 20 - 40 kg of fly-ash is produced (presuming the fly-ash is separately removed and not together with the scrubber residues) [27, 28, 37, 39].

Fly-ash cannot be reused or landfilled without further treatment, because of the high content of pollutants like heavy metals, which are easily leached out and organic matter (among which PCDD/F: 1 - 10 mg/kg [38, 42]). Furthermore fly-ash is easily blown away and dispersed by the wind if no measures are taken. This means that at least the fly-ash has to be immobilised e.g. by mixing with cement or by stacking it in big bags. At present, part of the fly-ash is treated likewise before landfilling, a part is used in road works (asphalt filler) and construction works (in concrete).

However the amount of pollutants is too high to meet the more severe regulations (already enforced or to be expected) for reuse or landfilling. Therefore several treatment processes are being developed.

At first the same processes as for bottom-ash can be applied: washing and/or melting. The last one can technically be combined with the melting of the bottom-ash. In this way PCDD/F or other organic material contained in the fly-ash is destroyed. For fly-ash only, other processes are of interest because these use less energy and possibly are more feasible: melting processes still under development; low temperature destruction of PCDD/F [44] and the 3R-process [45]. The first process has been demonstrated on pilot-plant scale [46], and will come into operation on full scale soon. In the 3R-process the acidic waste water from the first step of the scrubber is used to wash the fly-ash so that heavy metals are removed to certain extent. Then the fly-ash is dried, mixed with binder, pelletized and returned on the grate of the combustor, where PCDD/F and other organic matter is destroyed.

5.3 Scrubber residues

Residues of dry and semi-dry scrubbers mainly consist of salts. Dry scrubbers produce approximately 25 - 45 kg residue per ton MSW combusted, whereas semi-dry scrubbing results in 15 - 35 kg per ton MSW combusted [25, 27, 28]. So far there are no possibilities for reuse or recycling; these residues have to be landfilled, usually as a hazardous waste (high costs). Before landfilling the material is usually stacked in big bags or immobilised with cement or binder.

The waste water of a wet scrubber can be evaporated, resulting in 10 - 15 kg solid residue per ton MSW combusted [25, 27]. This can be implemented in the flue gas cleaning system or separately (see Figures 18 and 19). The treatment of the solid residues is the same as for the (semi-)dry scrubber residues: stacking in big bags or immobilisation and subsequent landfilling.

Another possibility is to remove the absorbed acid gases from the waste water as a salt or a concentrated acid. There are several methods depending on the absorbent used in the scrubber:

- a. If in the first step only water is used, the waste water is in fact a HCl-solution which, through recycling of the wash water over the first step, has a HCl-content of 7 - 9 wt%. To keep impurities like dust and heavy metals out of this HCl-solution, a quench has to be installed before the first step of the scrubber. In this quench a HCl-saturated solution is sprayed in the flue gases. On the bottom of the quench a slurry builds up which is removed, dried and landfilled (in big bags or with a binder). Other waste water streams can also be used in the quench. The HCl-solution is distilled to concentrated HCl (30 - 31 wt% solution) which can be sold commercially [34, 47]. Around 16.1 kg of concentrated HCl per tonne MSW can be produced this way [34]. The residues from the distillation are landfilled together with the residue from the quench. Instead of distillation, the HCl-solution can also be neutralised with $\text{Ca}(\text{OH})_2$ or NaOH which renders solids which can be separated. The remaining solution is evaporated. The first additive renders solid CaCl_2 which is difficult to market on a commercial basis. The second renders solid NaCl (10 - 20 kg/tonnes MSW [28]) which can be used in the chlorine-alkali-electrolysis process, which producing NaOH again and Cl_2 -gas. As there is an excess of Cl_2 -production already, this gas has to be burned then to HCl [34, 47, 48]. Despite these economical disadvantages, this process has been realised at two combustors in Germany: Stapelfeld and Iserlohn [47]. Another option is to use the NaCl in the production of soda-ash. This renders as a by-product CaCl_2 which has to be landfilled.
- b. If in the first step a $\text{Ca}(\text{OH})_2$ -solution is used, a CaCl_2 -solution is formed through absorption of HCl (10 - 20 kg per tonne MSW [28]). This CaCl_2 -solution can be treated with sulphuric acid resulting in a HCl-solution and solid CaSO_4 . The HCl solution can be distilled to marketable concentrated HCl. The solid CaSO_4 has to be washed and dewatered to produce gypsum. Part of the CaCl_2 -solution is removed, dried and landfilled (in big bags or fixated) to prevent building up of impurities in the recycled wash solution [47].
- c. If in the first step the HCl is removed, then in the second step the SO_2 can be removed with $\text{Ca}(\text{OH})_2$. This results in $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (gypsum) after washing and dewatering [34, 47]. In fossil fuel fired power station this technique is well established, thus making the marketing and sales of the (surplus) gypsum difficult.

5.4 Contaminated active cokes

As already presented in table 5, depending on the technique, 0.3 to 3.6 kg active cokes per ton MSW is used [25]. As this active cokes adsorbs almost every pollutant present in the flue gases, the used active cokes is consequently contaminated with all kinds of pollutants: organic compounds (among which PCDD/F, PCB, etc.), but also HCl, SO₂, dust and heavy metals. Several options are being suggested for final processing of this material, but as there are at present only a limited number of MSW combustors in operation in Europe, which have active cokes adsorption implemented in their flue gas cleaning technique, it is not clear yet, which solution is the most favourable.

All suggestions focus on combustion of the contaminated cokes, either in the MSW combustor itself (back on the grate or injected through a nozzle in the combustion chamber) [49] or in a separate combustor. Both schemes have its specific problems.

When the cokes is returned to the grate incinerator, special care has to be taken to prevent the small cokes particles (1 - 4 mm in diameter), from falling through the grate, or being entrained with the flue gas flow without being completely burned. The first problem might be smaller, if the material falling through the grate would be recycled to the grate. The second, however, will create serious problems, not only because the fly-ash quality decreases (more unburnt carbon, more PCDD/F), but also because of possible corrosion in the boiler (unburnt carbon can give rise to high local CO-levels and reducing conditions). In order to reduce entrainment, the spent cokes can be pelletized before feeding it on the grate. Whether this really is a solution is questionable, because in the burning process, the cokes-pellets split up again. On the other hand, if the pellets do not break up during combustion, they need a long residence time for complete burn-out. If this long residence time is not realised the bottom-ash quality is endangered (higher content unburnt carbon, and higher content PCDD/F).

All together feeding the cokes back to the combustor itself seems to create more problems than it solves.

Separate combustion of the cokes, of course has the disadvantage of additional investments. On the other hand it offers the possibility to design the device especially for the combustion of cokes. Furthermore the installation can be relatively small and process control probably is simple compared to a large MSW combustor, reducing the risk of calamities.

At present combustion of active cokes in a cyclone burner, a circulating or fluid bed or a rotary kiln, are considered to be viable solutions. The rotary kiln might enjoy the advantage that very easily switches to other waste feedstocks (chemical or clinical wastes) can be made.

At present spent active cokes is combusted in rotary kilns, designed for chemical waste combustion, however with quite a lot of problems. A different solution is the application of a dedicated cyclone burner; with this system experience is also limited.

6 Characterisation of the incineration status in selected countries

To illustrate the status of MSW incineration and the wide variation that exists in this field, the situation in a number of countries with regard to the present status and developments is given below. The selected countries are: Germany, USA and Japan. This selection is based on the fact that the situation and developments in these countries are quite different from each other.

Germany represents the countries with the most advanced technology in waste incineration and the associated environmental care. Other countries belonging to this group are Austria, The Netherlands and Switzerland.

There is a large variation in the second group of countries, where the applied technology (in general) is less sophisticated and environmental standards are (still) less stringent. The USA is presented as a representative of this group.

Japan is a country where a very large part of the MSW is incinerated (> 74%), the applied technology shows many differences with other countries.

6.1 Germany

Because there are still large differences in the field of municipal waste management between the former Western Germany (FRG) and the German Democratic Republic, in the following only Western Germany is considered.

The annual production of MSW, including the part of the industrial and trade waste that is processed in the same system, amounts to 25 Mton. Of this total around 36% is incinerated. A remarkable aspect of the total amount of MSW is, that it has been almost constant for the last few years.

Germany was the first country to introduce a law generally obligating the suppliers of goods to take care of the packaging material involved and to dispose of this material outside the existing MSW processing channels. This has been the basis for the so called 'Dual System' where a foundation with the same name is given the responsibility to practically carry out this policy on behalf of the collective producers/suppliers. The ultimate goal of this system is to reduce the amount of packaging material and to promote recycling of this material as much as possible. A basic problem that has been encountered already in the first phase of development of this scheme, is that it is difficult to give recycling e.g. of plastics a sound economic basis.

In the current waste management policy first priorities are prevention of waste generation and recycling of waste material. To avoid landfilling as far as possible, the incineration capacity (with energy utilisation) will have to increase considerably. At present there is still a strong public opposition against the expansion of the incineration capacity, although the very stringent environmental standards that have to be met might change this attitude in the near future. It is not yet clear how this will develop.

The average composition of the German MSW is presented in Table 6.

Inventory of international Municipal Solid Waste Incineration Technologies

Table 6 MSW composition in Germany (1990)

Category	Weight %
Paper /cardboard	24
Plastics	7
Glass	9
Textiles	2
Metals	6
Putrescibles/fines	44
Miscellaneous	8

Regulations to control the environmental aspects of municipal waste incineration were introduced early, namely the 'TA Luft' 1974, followed by a revision in 1986, and the '17.BImSchV' in 1990. Table 7 shows the emission limits according to the last two regulations. Also shown in this table is the anticipated state of the art in 1996 according to [50]. Existing installations will have to be retrofitted to comply with the 17.BImSchV before the end of 1996.

Germany is the basis of a number of large manufacturers of waste incineration installations. Together with the already mentioned environmental regulations this has caused the German waste incineration technology to develop to an advanced stage. This is demonstrated amongst others by:

- Several active cokes filters for PCDD/F removal are in operation.
- Catalytic oxidation of PCDD/F in a SCR reactor is in the demonstration phase.
- Low temperature destruction of PCDD/F on fly-ash is also in the demonstration phase.
- SNCR denox has been demonstrated.

Table 7 Emission standards for MSW Incineration in Germany and anticipated state of the art in 1996
(Figures of TA Luft refer to half hour averages, others to daily averages)

Components	Fluegas concentrations, mg/m ³ (11% O ₂)		
	TA Luft 1986	17.BImSchV 1990	Anticipated 1996
NO _x	500	200	< 70
TOC	20	10	< 4
CO	100	50	< 30
Particulates	30	10	< 3
HCl	50	10	< 3
HF	2	1	< 0.3
Hg	0.2	0.05	0.02
Cd + Ti		0.05	< 0.01
Heavy metals		0.5	< 0.1
PCB's		detection limit	detection limit
PCDD/F		0.1 ng I-TEQ/m ³ ₀	< 0.1 ng I-TEQ /m ³ ₀

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Beside this development of the 'conventional' technology, the growing complexity of these installations, caused by the increasing environmental requirements regarding emissions and residues, has been the reason for various new developments. In general these are based on (partial) pyrolysis or gasification, in an attempt to decrease the need for expensive 'end of pipe' technologies as far as possible.

Reference installations

By the rapid technological developments, that are going on in connection with the new environmental requirements, the technologies applied by the various manufacturers evolve continuously and in different directions. Consequently the installations presented here, might not be fully representative for the general situation. However, the examples show some of the complex systems that have to be applied in the 'thermal waste treatment systems', to fulfill all present and near future requirements simultaneously.

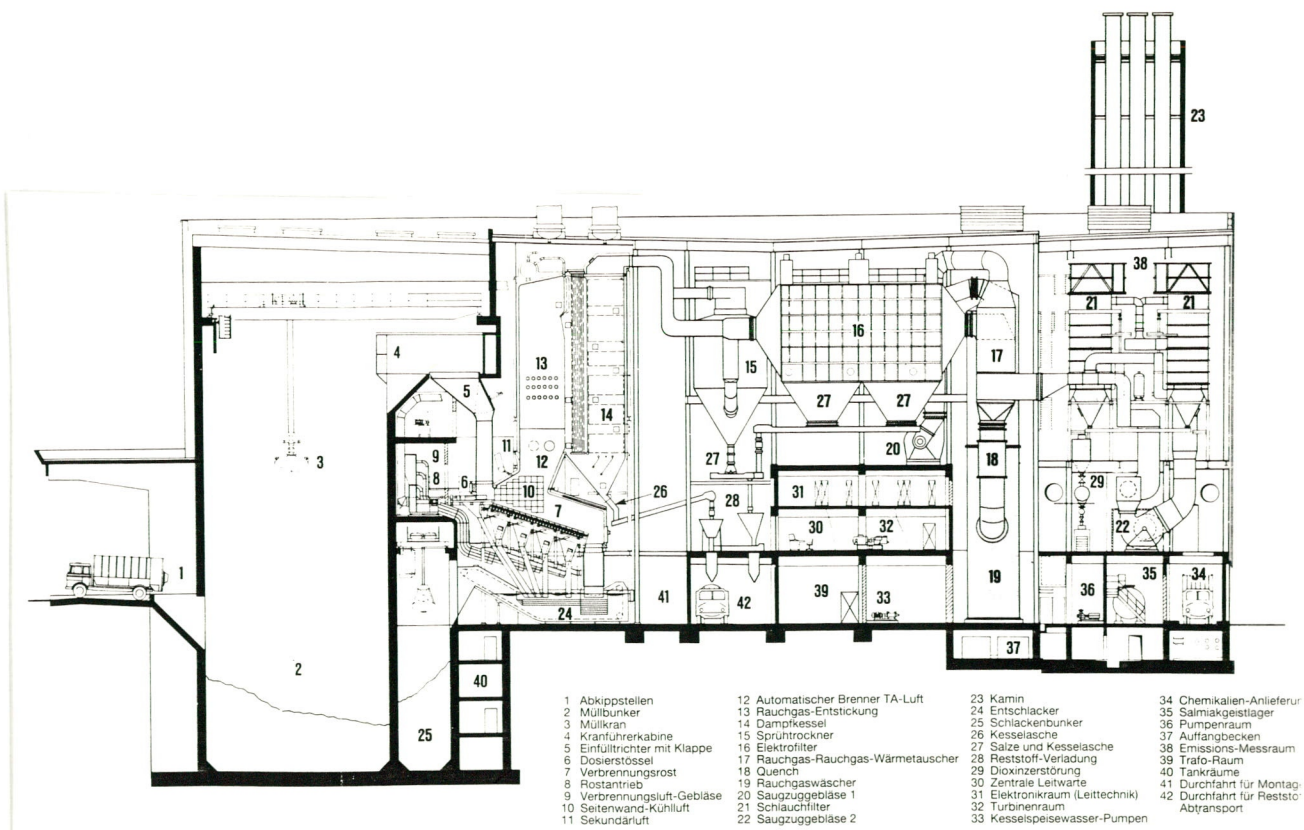


Figure 22 MVA Bonn

MVA Bonn [51]

In this installation (Figure 22), built by Von Roll, that started operation in 1992, 180,000 ton/year is incinerated (3 lines). The produced steam is used for electricity generation and district heating.

Characteristic data for this installation are:

- Reciprocating grate, primary, secondary and side wall cooling air;
- Capacity (based on 10 MJ/kg): 3×10 ton/hour;
- Temperatures: 850 - 1050 °C;
- Control input parameters: temperature, O₂ content, steam production;
- Steam conditions: 400 °C, 44 bar, 3×29 ton/hour;
- Flue gas cleaning system:
 - spray dryer (waste water free operation),
 - ESP,
 - three stage wet scrubber,
 - SNCR denox system,
 - entrained flow active carbon system incl. fabric filter,
 - Hagenmaier reactor to destroy dioxins in spent active carbon;
- Emissions: see Table 8.

Because the presented emission data are design figures, this table also shows measured data from the installation at Ingolstadt, which is equipped with a similar flue gas cleaning system.

The investment costs of the MVA Bonn have been around 175 M\$, corresponding to approx. 0.25 M\$ per (design) - ton/day.

MHKW Essen-Karnap [52]

This is an example of a relatively new installation (1987) that will be retrofitted with additional fluegas cleaning systems to comply with the last regulations.

The installation has an annual throughput of 560,000 ton, and consists of three grate incinerators with a capacity of 21 ton/hour each (based on 10.5 kJ/kg), manufactured by Deutsche Babcock (Figure 23). The produced steam can be used for electricity generation only (39 MW), or partly for district heating ($130 \text{ MW}_{\text{th}} + 10 \text{ MW}_{\text{e}}$).

Characteristics:

Steam conditions: 41 bar, 400 °C, 68.5 ton/hour

Grate: 6 rollers, diameter 1.5 m, width 5.5 m

Total bunker storage capacity: 22,500 m³

Fluegas cleaning system (present, see Figure 24):

- three stage ESP;
 - single stage wet scrubber, basically acting as a desulphurisation unit, with saturator and Ca(OH)₂ injection;
 - waste water cleaning system with supply of lime, flocculating agents and TMT15 (to capture Hg); solid residues from this process (containing heavy metals, particulates, Fluorides etc.) are separated, dried and landfilled as hazardous waste.
- The flue gas emissions are presented in table 8.

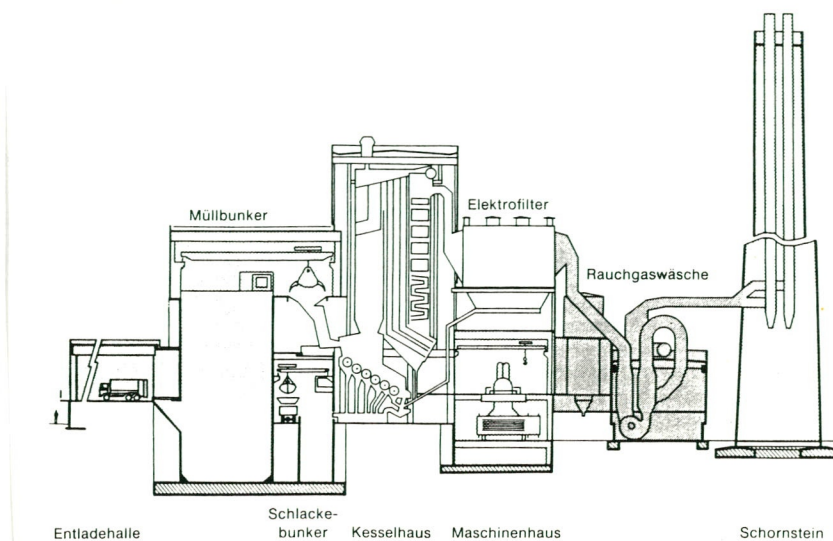


Figure 23 Cross section of the Essen Karnap installation

To comply with the 17.BImSchV the fluegas cleaning system has to be improved.

To select the most appropriate system, to be added to the scrubber, a large test programme with slipstream units with capacities ranging from 400 to 2000 m³/hour has been carried out [53]. Systems that have been tested are:

- a fixed bed reactor with active coke;
- a catalytic oxidation technology;
- additive supply in an entrained flow reactor with fabric filter.

It was concluded that both adsorption systems will need a catalytic technology to reduce NO_x emissions and that the catalytic system will need an adsorptive cleaning stage to reduce Hg and SO₂ emissions.

Not all aspects that are relevant in the full scale application of the various systems have been tested. Nevertheless, based on the results of these tests, some designs, that had initially been offered for the retrofit, had to be adapted considerably. For the final selection of the new system, site specific conditions, additional reduction potential and complexity of the installation have been deciding factors. The new installation will be based on the fixed bed active coke technology.

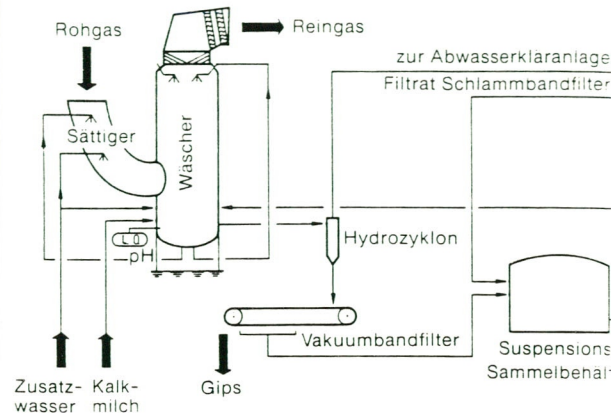


Figure 24 Flue gas cleaning system

MVA Ludwigshafen [16]

This facility, consists of one older (1967) incinerator and two units that started operation in 1989. The two new units have a capacity of 12 ton/hour (based on a heating value of 8000 kJ/kg) and have both been built by Deutsche Babcock. It is a parallel flow design with a roller grate (Figure 25).

In the design, the environmental properties of the primary process have played an important role. The combustion temperature is relatively high, namely 1050 °C, with a minimum residence time of the hot gases of 2,5 s. To achieve this, the air ratio is < 1.8, combustion air is pre heated up to 200 °C, the walls in the combustion area are insulated and additional firing of auxiliary fuel is possible in case of waste with a low heating value. The airflow in the combustion chamber has been designed in a way that, with the help of the secondary air injection, a strong circulation is created, to increase the residence time of particulates in this area, increasing the combustion efficiency.

Steam conditions in the boiler are 450 °C, 43 bar; the achieved boiler efficiency is around 79%.

Flue gas cleaning system (see Figure 26):

- spraydryer, (waste water free operation);
- ESP;
- two stage wet scrubber.

Initially a denox system using NaClO₂ has been installed, because of improper operation this system has been taken out of operation. To get the required Hg reduction, TMT15 is supplied to the SO₂ scrubber.

The fluegas emission data, at the boiler exit as well as in the stack are presented in table 8. These data show that except for dust and NO_x, the requirements of the 17BImSchV are met.

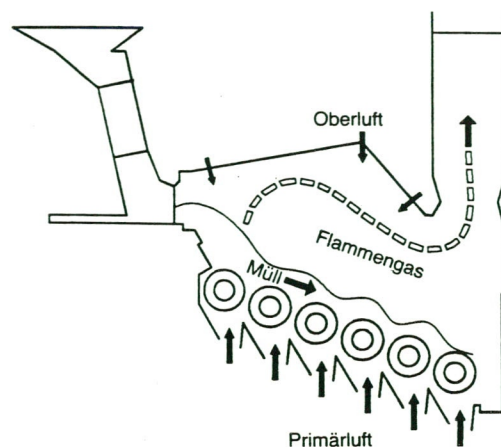


Figure 25 Schematic cross section of the combustion chamber

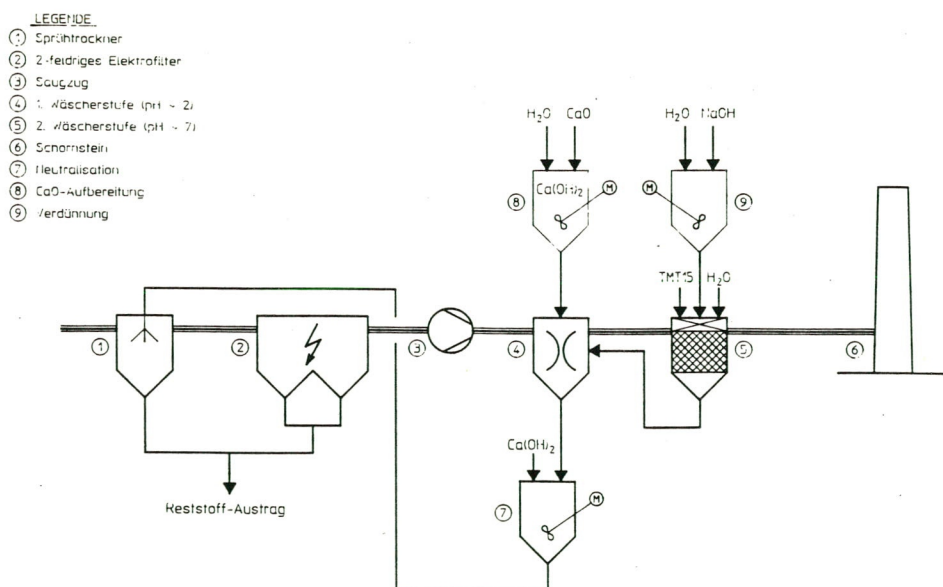


Figure 26 Schematic diagram of Ludwigshafen flue gas cleaning system

MVA Hamm [54]

This facility, dating from 1985, consists of 4 lines of grate incinerators (three operating simultaneously). The annual throughput is 245,000 ton. The average capacity of each unit is 9.4 ton/hour, based on a heating value of 8800 kJ/kg.

The units are equipped with a horizontal grate (K+K), it is a intermediate flow design. The steam production of each unit is 24 ton/hour (400 °C, 40 bar). The original flue gas cleaning system consisted of a cyclone, a spray adsorber followed by a fabric filter; residence time requirements were 0.3 s above 800 °C.

In 1993 a complete reconstruction of the installations (by the company Noell) has been completed. The basic design of the incinerator has not been changed, but many of the components have been improved on basis of the operational experience and new requirements.

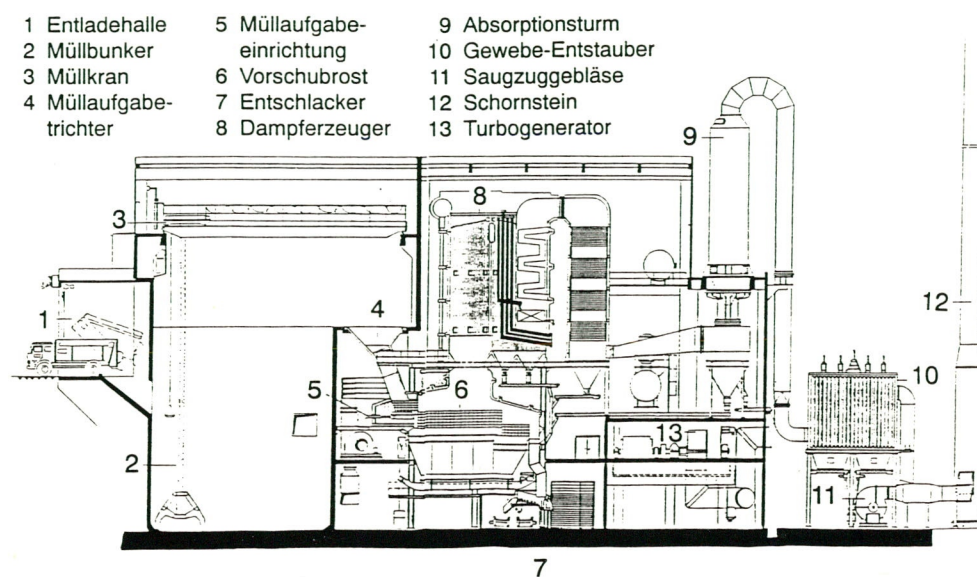


Figure 27 Cross section of the Hamm installation

The improvements include a.o.:

- Mechanical alterations to the grate
- Improvement of the combustion area geometry and insulation of the walls of the first draft to comply with the requirement concerning the 2 s residence time above 850 °C
- In order to detect changing waste properties faster and more accurate, and to properly react on these changes, the control system is now using a number of additional input parameters, like:
 - the hydraulic pressure in the separate grate actuating systems, that is a measure for the waste mass on the respective sections .
 - more temperature measurements in the combustion chamber
- Regarding the flue gas cleaning , the existing system has not yet been changed. To reduce the NO_x emission, preparations have been made to install a SNCR system. For increased reduction of dioxin emissions, tests have been carried out to supply active coke containing additives. Dioxin levels significantly lower than the limit of 0.1 ng TE/m³ have been demonstrated with this system. Emission levels recorded in the new situation are presented in table 8.

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Table 8 Emission performance data of some German MSW incinerators

Components	Fluegas concentrations, mg/m ³ (11% O ₂)				
	MVA Bonn (required)	Ingolstad (3) ¹⁾ (1993)	Hamm (1993, average)	Essen-Karnap (1990)	Ludwigshafen (1990)
SO ₂	30	< 1.0		44	20
NO _x	100	approx. 40	200	398	280
TOC	10	< 1	< 2	< 1	< 1
CO	50		12	29	6.3
Particulates	10	< 1.5		3.3	13
HCl	10	< 1.0		1.8	8.4
HF	0.5	< 0.02		0.3	0.6
Hg	0.05	< 0.009		0.02	0.044
Cd	0.05	< 0.001		0.006	0.002
Heavy metals	0.5			0.17	0.127
PCDD/F ng/m ³ TEQ	0.1	< 0.02	< 0.08	1 - 3	< 0.6

¹⁾ Flue gas cleaning system comparable to MVA Bonn.

Berlin Ruhleben

This large facility with 7 grate incinerating units is at present expanded with a fluidized bed incinerator of the Ebara/Rowitec design with a capacity of 10 ton/hour.

According to the design, no additional measures are required to meet NO_x emission levels around 150 mg/m³. On the other hand, a quite elaborate system, incorporating a spray dryer and two stage wet scrubber is used to reduce SO₂, HCl and HF to the required level.

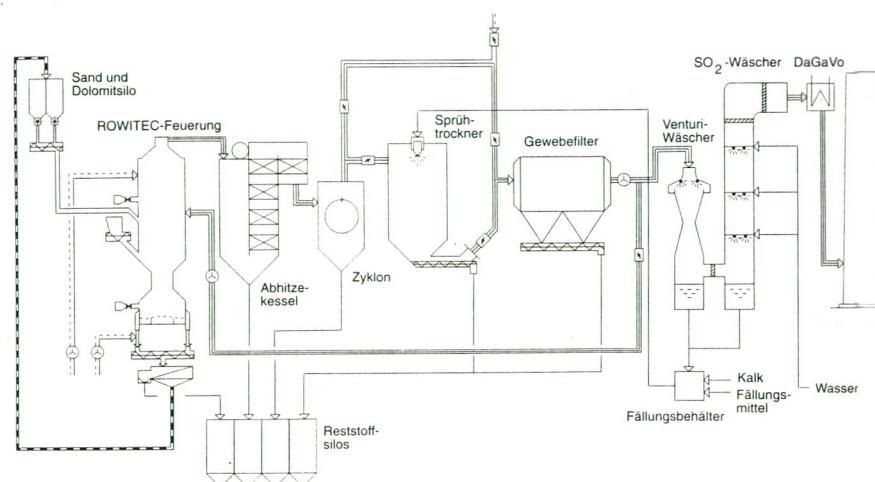


Figure 28 Schematic diagram of the Berlin Ruhleben fluidized bed incinerator under construction

6.2 USA

Apart from the exact definition of MSW, apparently the estimates concerning MSW generation in the USA vary widely [55]. For example, models used by EPA estimate that in 1990 the residential, commercial and institutional sectors generated approximately 180 Mton of refuse. According to a different source this figure should be over 293 Mton. As a basis for the 'Energy from Municipal Waste Program' plan of the Department of Energy, it is assumed to be 250 Mton. Of this total, around 35 Mton is thermally processed: 32 Mton/a in installations with energy recovery ('Waste To Energy' plants), 2 Mton/a in incinerators without energy recovery ('Incinerators') and 1.6 Mton/a in RDF plants. According to [56], 2 facilities are currently under construction (capacity 0.9 Mton/a), 37 facilities are in the planning stage and 9 are not operating (total capacity 15 Mton/a). Table 9 gives a breakdown of the operating installations to type and capacity.

Table 9 Operating MSW Combustion plants in the USA [57]

Technology	Number of operating plants	Daily design capacity (TPD)	Annual capacity Million tons
Modular	48	5283	1.6
Mass burn	65	65534	20.3
RDF	29	30460	9.5
WTE Facilities (total)	142	101277	31.4
Incinerator	34	6957	2.2
Total US Plants	176	108234	33.6

Approximately the same amount that is incinerated is disposed of by recycling and composting [57]. The current policy is to increase this amount considerably. Often recycling/sorting facilities (Material Recycling Facilities) are combined with incineration facilities. There are several reasons for this policy, ranging from lack of landfill space, problems to site new incineration facilities because of public opposition, and concern about the environmental effects of the alternatives.

The average composition of MSW, according to a 1992 update [58], is presented in table 10.

Table 10 Average MSW composition in USA, 1992 [58]

Category	Weight %
Paper/cardboard	37
Glass	7
Plastics	8+
Textiles, rubber, leather	5
Metals	8
Yard trimmings	18
Wood	6
Food	6
Miscellaneous	3

Inventory of international Municipal Solid Waste Incineration Technologies

The present environmental standards for MSW incineration apply to the larger installations only. A draft of new standards for smaller installations (capacity above 39 ton/d) and with more stringent limits for larger installations (capacity above 250 ton/d) has been presented [59]. The present and proposed limits are given in Table 11. As can be seen, these limits are less severe than those in some countries in Western Europe (Table 4 and 7). A number of components that are not covered explicitly by the standard are considered to be controlled by the obligation to apply 'good combustion practices' and also the 'best demonstrated technology' (BDT). In the existing legislation this means that, e.g. to limit dioxin emissions, for the largest installations a spray dryer and an ESP (or a more sophisticated system) shall be applied.

In the proposed new standard special emphasis is on control of heavy metals, particularly Hg.

Table 11 Current and draft (new) emission standards

	Current standards		Draft rules	
	Large 251-1100 TPD	Very Large 1100 TPD+	250 TPD+	39-250 TPD
Capacity				
Opacity %	10	10	10	10
Particulates	69	34	34	69
SO ₂ ppmv or	30	30	30	700
SO ₂ % reduction	50	70	85	--
HCl ppmv or	25	25	25	1000
HCl % reduction	50	90	95	--
NO _x ppmv	--	--	500	500
Organics ¹⁾ ng/m ³ ₀	125	60	30	500
Fugitive dust, opacity (ash handling) %	--	--	0	0
CO ppmv (modular plants)	50	50	50	50 - 250
CO ppmv (mass burn Waterwall)	100	100	100	--
CO ppmv (RDF)	200	200	200	--
CO (mass burn rotary)	250	250	250	--
Cadmium mg/m ³ ₀	--	--	0.02 or 0.04 ²⁾	0.1
Lead mg/m ³ ₀	--	--	0.16 or 0.50	1.6
Mercury mg/m ³ ₀	--	--	1.50 or 0.10	1.5

¹⁾ Total dioxins and furans.

²⁾ An optional set of standards relaxes the limits for cadmium and lead, but tightens mercury to 100 micrograms.

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Reference installations

The present state of the art in MSW incineration might be best illustrated with the data from [60]. Here 8 recently constructed facilities are surveyed, a.o. with regard to emission performance. All these installations apply spray dry adsorbers either in combination with an ESP or with a fabric filter. All installations have to comply with different (state depending) emission limitations. It appears that all facilities comply with their respective regulations. The average emission performance data are compiled in Table 12.

All facilities generate electricity, ranging from 9 MW at Peel, Ontario to 66 MW at Broward County. The capital investment costs of the facilities range from around 0.1 to 0.25 M\$ per ton/day, tipping fees are between \$63 and \$86 per ton.

Table 12 Emission standards and average emission performance data (standards in brackets)

Facility/ Developer	Capacity ton/day	Start of operation	Average concentration mg/m ³ ¹⁾						
			DUST	SO ₂	HCl	CO	NO _x	Hg	Cd
Broward / Wheelabrator	2250	1991	1 (50)	4.8 (240)		26 (154)	780 (1000)	(1.7)	
Camden/ Foster Wheeler	1050	1991		81 (203)	11 (110)	(175)	575 (860)	(36 g/h)	
Huntington/ Ogden Martin	750	1991	2.4 (32)	208 (365)	66 (110)	66 (175)	395 (540)	(0.4)	0.045
Preston/ American Ref Fuel	600	1992		(203)	2.2 (110)	88 (420)	640 (1020)		
Montgomery/ Montenay Power	1200	1992		36 (120)	17 (67)	14 (175)	525 (860)		
Adirondack/ Foester Wheeler	400	1992	10 (82)	68 (340)	53 (190)	119 (660)	470 (810)	(2.4)	
Peel/ PRRI	450	1992	8.8 (40)		53 (93)	4 (122)			
Mid Maine/ American Energy	200	1992	(32)	54 (120)	(56)	2 (175)	710 (1000)		

¹⁾ The averaging period is 1 hour in most cases, sometimes 3, 8 or 24 hours, or in case of SO₂ at Adirondac even 90 days.

6.3 Japan

The situation in Japan regarding Municipal Solid Waste disposal is strongly affected by the specific geographic conditions. Because only a small part of the surface area lends itself to useful purposes, the population density in the urban areas is very high and free space is scarce and expensive. This is one of the reasons that, in order to obtain the largest mass and volume reduction, a large part of the waste is incinerated.

Since the mid seventies more emphasis has been put on separation, recycling and reuse of waste.

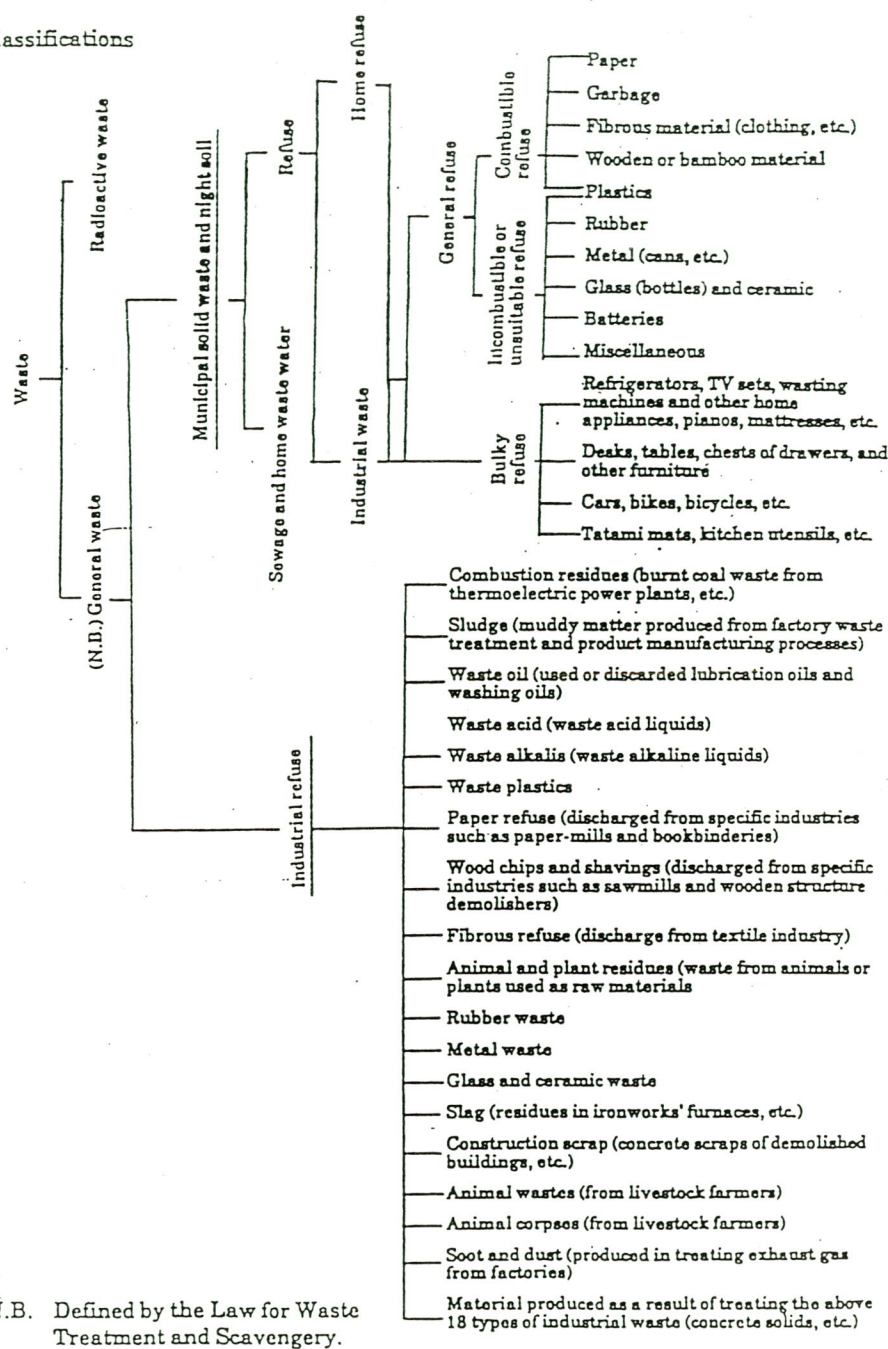
In 1991 the Waste disposal Law, the basis for the waste disposal policy and dating from 1970 was revised to incorporate the presently accepted waste management hierarchy:

- Prevention of waste generation;
- Waste minimisation;
- Reuse and recycling;
- Sanitary disposal.

The classification of waste, as applied in this law is presented in Figure 29. The position of plastics in this scheme is not a coincidence. In the older incinerators, designed for a specific maximum calorific value of the waste, the increasing amount of plastics leads to a higher value than acceptable. Under these circumstances plastics are considered as a material that should not be combusted and therefore landfilled directly. Another reason not to incinerate plastics in cases where an appropriate fluegas cleaning system has not (yet) been installed may be the effect on HCl emissions. The newer installations are designed for a higher heating value, so in these installations plastics can be categorised under the combustible material.

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Waste Classifications



N.B. Defined by the Law for Waste Treatment and Scavengery.

Figure 29 Classification of waste in Japan

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The amount of MSW generated in Japan is approximately 1.1 kg/capita per day, resulting in a total amount of MSW of 150 Mton/a to be disposed of. Of this total over 74% is incinerated, 20.4% is landfilled directly and around 5% is treated otherwise, mainly by composting (see Figure 21). Including combustion residues ultimately 34% is landfilled.

The percentage of waste that is incinerated is much higher than in the USA and in Western Europe and is still rising; the target is 80%, to be reached in 2010 [61].

Of this collected waste 4.6 Mton/a, mostly consisting of ferrous metals, aluminium, glass and paper is recycled through sorting (manual and magnetic) from non combustible and bulky waste. The figures do not include materials recycled through various source separation schemes which get much attention at municipality and community level [62].

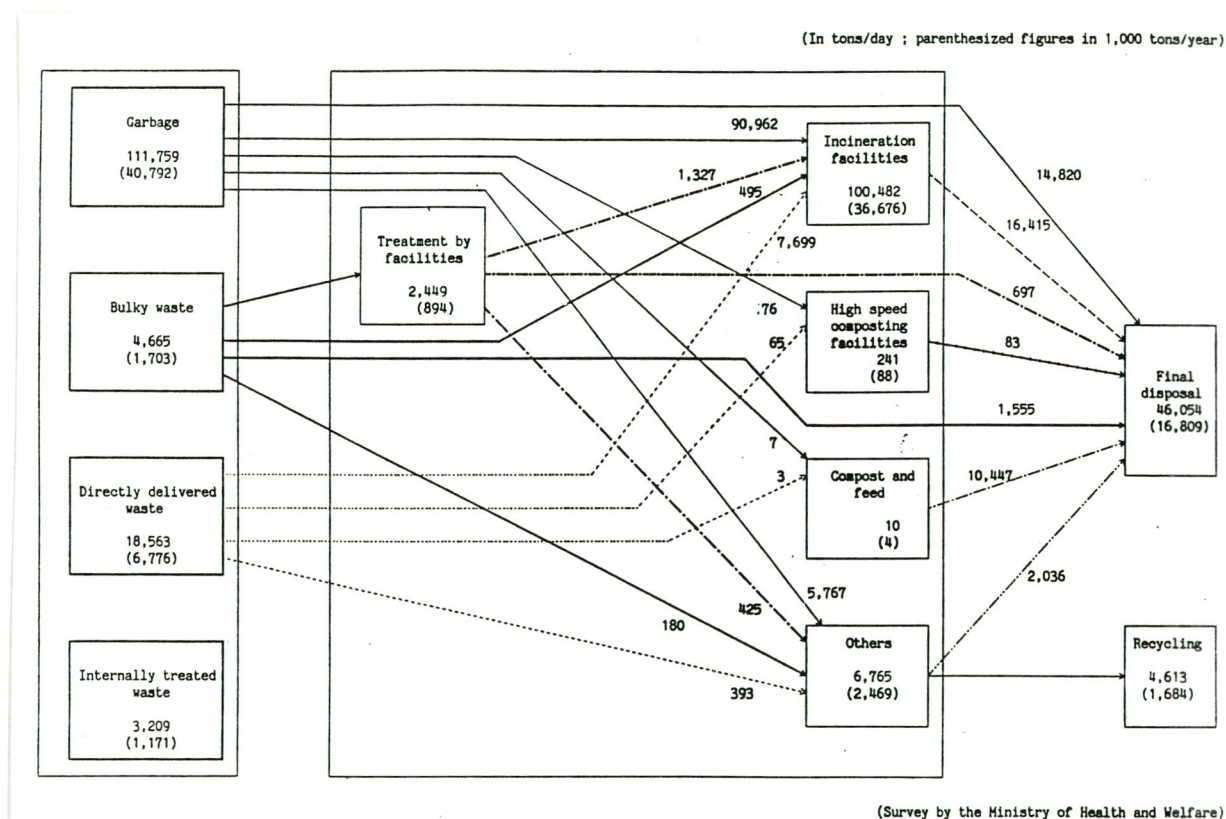


Figure 30 Waste handling in Japan

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MSW Composition

The amount of MSW in Japan roughly corresponds to that in other industrialised countries, the average composition is somewhat different; the paper and plastic content are relatively high, the putrescible fraction is relatively low. A number of results from waste composition analyses are collected in Table 13. The figures in this table, assembled from different sources [62, 63, 64], are not fully compatible because of non-uniform categorisation. Nevertheless they provide a fairly accurate general view of the waste composition.

Table 13 MSW Composition in Japan

Category	Weight % (Dry Basis)		
	Tokyo (sorted)	Osaka (unsorted)	Kawasaki (1989)
Paper	45.6	33.4	34.2
Garbage		5.7	
Putrescible			7.6
Wood and bamboo	9.9	8.4	2.8
Textiles, fibres	3.9	5.0	3.7
Plastics	8.1	21.4	13.7
Glass + Ceramics	1.0	6.3	14.5
Metals	1.3	5.8	6.9
Miscellaneous (comb.)	30	14.0	6.4
Miscellaneous (non-comb)		1.2	
Moisture content	44.4	41.8	
Ash content	7.3	15.5	16.0
Lower Heating Value GJ/ton	8.5	8.7	9.0

Incineration technology

Around 1900 incinerators are in operation to process 100 Mton/a. The average size of the installations is approximately 50,000 ton/a. This relatively small size can be explained by the policy that most of the MSW is incinerated locally near the area where it has been generated. It is quite common that the installations are built centrally in residential areas. In Kawasaki e.g., an industrialised city with 1.2 million inhabitants, 5 facilities with a total capacity of 3150 ton/d are in operation. Although, just like everywhere else, people do not like to have an incinerator in their neighbourhood, it is made more acceptable to them by giving certain facilities for free, in connection with the siting of such an installation, like a swimming pool. Also these installations are built in a way that the whole operation takes place inside a building, so that, apart from the transport, there is no nuisance like noise and bad smells to the people living near the facility. Apparently, in the Japanese society this system works reasonably well.

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The emission standards for specific installations depend on the local situation and will usually be the result of negotiations between the operator of the facility and the community. The national standards, shown in Table 14, are relatively permissive and might be considered as minimum requirements. These are used by the local authorities as a basis for the standards for a specific new installation, that will often be more stringent. There is no general obligation for existing installations to comply with these standards within a certain period. However the increased recycling and separation effort, as a side effect, also improves the emission characteristics of these installations.

Table 14 National Japanese emission standard for MSW Incineration

Component	Guideline	Characteristic level
CO, mg/m ³ ₀	50 - 200	1 - 1000
HCl	700 (30 - 325) ¹⁾	8 - 650
SO _x	K ²⁾	30 - 350
NO _x	500 (100 - 300) ¹⁾	100 - 400
Dust	80 - 500 (50 - 100) ¹⁾	1 - 500
Hg		0.05 - 0.5
Cd		0.01 - 0.1
Dioxin (TEQ), ng/m ³ ₀	0.5 ³⁾	0.1 - 100

¹⁾ Limit value set by local authorities.

²⁾ K is a factor depending on stack height and background level of SO₂ concentration in the area.

³⁾ Recommended target value.

The grate incinerators, which have the largest market share, are mostly based on European designs by licensing agreements, e.g. Mitsubishi-Martin, NKK-Volund. Usually these designs incorporate specific Japanese developments, like the 'dual-flow' NKK incinerator (Figure 31), claiming to improve combustion efficiency and decrease NO_x emissions [62].

The applied flue gas cleaning systems at least consist of an ESP, often combined with a dry or wet scrubber. Denox systems are presently added to many systems. The national government supports investments for incineration facilities (30% of the costs). On the other hand, because there are no obligations for existing installations to comply with more stringent new standards, the adaption to these standards depends on the political will of the local authorities/operators. Because of the well developed separation schemes the emission characteristics of the older installations are relatively satisfactory. In some cases this is further enhanced by intensive mixing of the waste stream, e.g. in Kyoto a 10000 m³ bunker is part of an installation with a capacity of 600 ton/d.

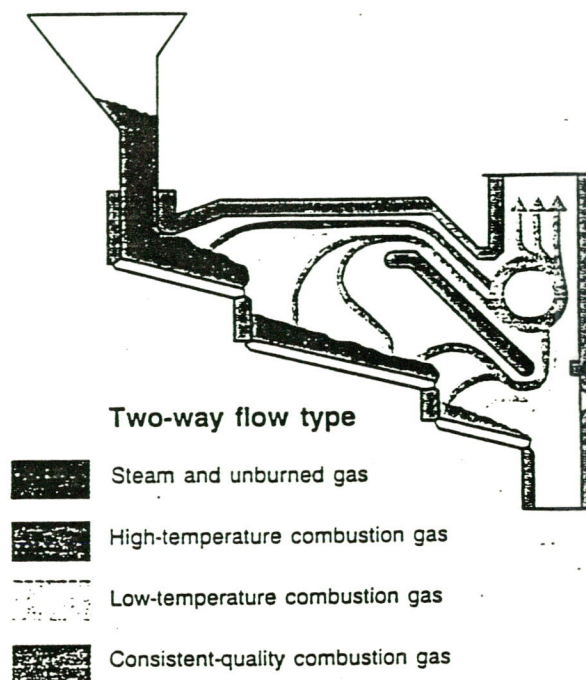


Figure 31 NKK Inc. dual flow design

Many of the smaller installations are operated 13 or 16 hours a day (2 shifts). This is also one of the reasons for the relatively high number of Fluidised Bed Incinerators, of which type over 100 units are in operation. It is obvious that this type of installation, if there are no severe requirements concerning the ashes, moderate emission standards and a low metal content in the waste, compares favourably to other systems in case of intermittent operation.

Ebara has a special design, the so called revolving type, to extract non-combustible material from the bed ash. This company has installed the largest number of these installations so far (approx. 40%). Other manufacturers like Mitsui, UBE, Hitachi and NKK apply the more conventional stationary FBC, combined with a front end shredder. Mitsui is also developing a system based on preparation of RDF pellets to be incinerated in a Circulating FBC in cooperation with the German company Lurgi [65].

Although FBC incinerators can operate with relatively low acid gas emissions by limestone injection in the bed, more severe emission limitations require the use of end of pipe technologies. E.g. the Ebara revolving bed installation at Funabashi, uses a semi dry scrubber to remove HCl and SO₂. Reported emission figures are: HCl 30 mg/m³, SO_x 140 mg/m³ and NO_x 210 mg/m³, while the combustion efficiency is as high as 99.5%.

Energy

Almost all incineration facilities use the energy that is generated by the combustion process; up to now this is mostly for heating purposes. Only a small part of the available energy is converted to electricity. This is caused by a number of reasons:

- up to very recently the price for electricity delivered to the public grid was very low;
- due to the very conservative steam conditions in the boiler (typically below 300 °C), the efficiency of electricity production is low (10 - 15%);
- the scale of the installations is relatively small. Around 100 installations are presently producing electricity with a total capacity of 320 MW. Almost half of these facilities deliver surplus electricity to the grid.

Residues

Most of the ash residues are landfilled. Utilisation of ashes is limited. The increased concern about leaching of heavy metals from the residues has recently resulted in various ash inertisation systems being applied, mostly based on ash melting or solidification with cement. Although the electricity consumption of the melting process is around 500 kWh/ton of ash, representing a substantial part of the electricity production potential of the waste, this system is often incorporated in new installations and retrofitted to existing installations.

Developments

A major development program has been started by NEDO in 1991 to develop a high efficiency waste incineration power plant. Testing and evaluation of the various designs developed in this program should be complete in 1997. One of the main aims is to be able to increase the steam conditions in the boiler of the incinerator to a level of 500 °C as one of the measures to reach 30% efficiency. Development of a high corrosion resistant superheater is considered as one of the most important steps in this plan.

7 Conclusions

- It is a common opinion from experts all over the world that an appropriate way to deal with non recyclable combustible Municipal Solid Waste, considering the present state of the art, is incineration with energy recovery. It can be concluded from this review that incineration, even with the most stringent environmental standards is technically feasible, by applying available flue gas cleaning (and residue treatment technologies if required).
- Several (tail end) technologies have to be used simultaneously, to comply with the most stringent emission standards for all relevant components. Therefore these new or retrofitted installations are quite complex and expensive.
- Components like HCl, dust and heavy metals have to be removed by tail end systems. The generation of components like CO and TOC can be prevented by optimisation of the combustion process itself. For components like NO_x and PCDD/F a combination of tail end systems and improved combustion conditions is the best approach.
- Development activities nowadays are focused on:
 - optimisation of the combustion process by improving the mixing intensity and by process control;
 - improving flue gas cleaning components like application of active cokes and combined NO_x and PCDD/F removal in a SCR reactor;
 - development and demonstration of residue treatment technologies like improving the quality of bottom-ash and fly-ash and the recovery of saleable salts from scrubber liquids.
- There are large differences between various countries with regard to the share of MSW that is incinerated. This also applies to the energy and environmental standards of the utilised installations. Moving grate incinerators are still the most applied technology for mass burning. Only in Japan the FBC technology is of importance. With increasing calorific value of the waste to be combusted, this relation may change in favour of the fluid bed technology.
- Often there is still much public resistance against incineration partly based on poor environmental performance of incinerators in the past. This will only change if the public can be convinced that the more advanced installations to be built according to the present state of the art are indeed harmless.
- Maximum utilisation of the energy that becomes available by incineration of MSW partly compensates for the treatment costs and saves a large amount of fossil fuel. A lot of improvement is still possible regarding this aspect.

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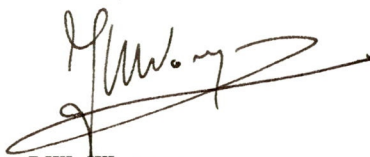
Names of establishments to which part of the research was put out to contract

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Date upon which, or period in which, the research took place

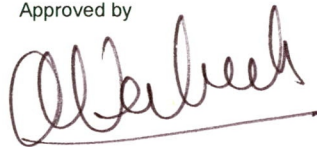
November 1992 - September 1993

Signature



J.W. Wormgoor
project manager

Approved by



A. Verbeek
head of department