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TNO-report

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The impact of a change in EC legislation on the combustion of municipal solid waste

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Summary

Municipal Solid Waste (MSW) combustion has been discussed intensively over the last two decades. As a result of this over the last five years changes in regulations, equipment and techniques used have come very rapidly. In Europe several countries have adapted these changes in different degrees and the overall situation is not clear.

At the moment the Commission of the European Community, DG XI is planning to revise the two directives on municipal solid waste combustion which were drawn up in 1989. Before doing this, however, the impact of such a revision on the present and future combustion facilities in Europe is to be determined. This is done in two steps:

a. Assessment of the present and future situation concerning municipal solid waste combustion facilities.
b. Technical and economical consequences for adapting existing and new municipal solid waste combustion facilities to a stricter (EC) directive.

These two steps were assigned to TNO and are reported here.

As to the first step, a database was drawn up on existing MSW combustion facilities, including technical information on these facilities such as the capacity, the flue gas cleaning system and the way of energy recovery. Except for a number of installations in France and Italy this database is complete. Information on the future development of MSW combustion, however, was scarce, fragmented and uncertain. The latter is mainly caused by public opposition to new MSW combustion facilities: this often changes or postpones the plans.

For the second step, first a description was set up of the technology which would be able to meet the demands of the EC Directive on HWC (Hazardous Waste Combustion). This was considered to be possible with a state-of-the-art combustion facility. Starting from a description of this state-of-the-art technology in MSW combustion the measures were described which would be necessary to adapt an existing facility to the level of the EC Directive on HWC, depending on the flue gas cleaning equipment which is already installed.

The investment cost for a new MSW combustion facility, based on state-of-the-art technology, was calculated. A facility with a capacity of 63,000 tonnes per year would require an investment of 90 to 110 million ECU, depending on whether the waste water can be discharged simply or has to be evaporated. This would then result in a processing cost of 229 to 279 ECU per tonne of waste combusted. For larger capacities the investment costs and processing costs per tonne decrease. For a capacity of 806,000 tonnes per year the investment cost ranges from 500 (waste water discharge) to 660 million ECU (waste water evaporation). The related processing costs then are reduced to respectively 92 and 124 ECU per tonne.

Besides describing how retrofitting of existing facilities could be done, also the cost involved were calculated for different capacities. Retrofitting to the emission level of the Directive on HWC appeared to require an investment of 14 to 30 billion ECU for Europe, depending on whether:

- waste water can be discharged in a river or sea, or has to be evaporated;
- dry and semi-dry scrubbers are capable (after upgrading) of reaching the required emission limits or need to be replaced by a (2-staged) wet scrubber.

These investment costs would result in additional processing costs of respectively 52 ECU (waste water discharge) and 114 ECU (evaporation of waste water) per tonne. Within Europe the investment costs for retrofitting vary a lot between countries. In Austria no investment is necessary because both combustion facilities are capable of reaching the required emission limits already. However France would have to invest over 7 billion ECU to retrofit all the MSW combustion facilities. The countries with the highest investment per tonne MSW for are France, Italy, Spain and the United Kingdom. Retrofitting Austria, Germany and the Netherlands would have relatively low investments per tonne. The other countries would have intermediate investment costs.

In fact the cost for retrofitting will be lower as some of the combustion facilities will never be retrofitted, but will be closed as soon as they have to meet emission limits which they cannot reach. However to maintain the capacity this will need investment in new facilities, which are generally higher.

By retrofitting all the existing facilities the emission of pollutants is reduced considerably. After retrofitting the emission of dust, HCl, HF and PCDD/F (polychlorinated-dibenzo-para-dioxins and -furans) will be around 1 to 2% of their present emission. SO_2, Hg, Cd and the rest of the heavy metals will be reduced to respectively 10, 19, 13 and 5% of their present emission level.

The calculation of the emissions and the investment and processing costs required a number of assumptions. These assumptions had to be made in order to be able to execute these calculations. Therefore these calculations should be considered as indicative and not as exact.

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1 Introduction

Combustion of municipal solid waste (MSW) has been a 'hot' item for the last decade. Not only because it is a sensitive subject for public and politicans but also because the technologies for MSW combustion have been changing rapidly during the last five years.

Ever since the discovery of PCDD/F (polychlorinated-dibenzo-para-dioxines and -furanes) in the flue gases of a an MSW combustion facility [Olie et al, 1977] emission legislations have been drawn up and have been made stricter, requiring more advanced techniques and equipment for combustion and flue gas cleaning.

In 1989 the EC (Directorate General XI) set up two directives on the combustion of MSW. However, at this moment some European countries have national guidelines which are a lot stricter than the EC directive: e.g. Germany, The Netherlands and Austria. As these last three guidelines more resemble the emission levels of what today is possible with state-of-the-art technology than the EC directive, the EC plans to update the 1989 directives. The 1992 directive for hazardous waste combustion (HWC) [European Directives, 1992] serves as an example of what the new directive for MSW combustion will look like.

However, before such a new directive is introduced the EC wants to know the impact of such a directive on existing and new MSW combustion facilities. Therefore TNO Institute of Environmental and Energy Technology has been assigned a study to examine this impact.

The study roughly consists of two phases:
a. Assessment of the present and future situation concerning municipal solid waste combustion facilities.
b. Technical and economical consequences for adapting existing and new MSW combustion facilities to a stricter (EC) directive.

In this report the results of both phases are presented.
First in chapter 2 the state-of-the-art technology is described for new MSW combustion facilities. Chapter 3 describes the retrofitting of existing facilities. In chapter 4 an overview is given of MSW combustion data in Europe (the total of the countries considered in this study), such as the amount and composition of MSW, the way this MSW is treated, the emission guidelines, what combustion facilities are in operation and what will happen in the future. Detailed data per country are given in Appendix A. In chapter 5 a total emission for the existing MSW combustion facilities in Europe is calculated and in chapter 6 the costs for retrofitting the existing installations to an emission level of the EC Directive on Hazardous waste are calculated as well as the costs for new facilities at this emission level. Besides investment costs also costs per tonne MSW are considered. Finally in chapter 7 the conclusions are presented.

2 State-of-the-art municipal solid waste combustion

The definition of 'state-of-the-art' for a certain technique is not automatically clear. In this study the 'state-of-the-art' is defined as the technology which has been proven in real-world applications today on a large scale and which can be built right now. A good technique now does not necessarily define the long-term position, merely what is considered to be 'the best'. Future developments and improvements may occur.

Though there are many different types of combustors which are used for municipal solid waste (MSW) combustion, this state-of-the-art description is confined to moving grate combustors, because these are the most commonly used. In addition fixed grate (small quantities), fluid bed (small quantities, sludge) and rotary kiln combustors (mainly chemical or toxic wastes) are also used.

Furthermore this description below assumes that heat is recovered through steam production in the boiler. Again this is the most common system.

Figure 1 is a schematic presentation of an MSW combustor.

The first objective of waste combustion is to reduce the weight and volume of the waste and to increase the inertness (minimise the leachability and the toxicity) of the residues which have to be landfilled. This must be carried out with the least possible emission of pollutants. Secondly the maximum amount of energy should be recovered from this process.

2.1 Waste as a fuel, mass burn, waste pretreatment

Several MSW combustion options are possible. Besides direct burning the MSW completely as it is delivered (mass-burn) several fractions can be preseparated from the waste for alternative treatment: recycling, composting or landfill. This ranges from the separation of metal scrap for recycling to the production of a high calorific waste fraction (RDF: Refuse Derived Fuel) for use as a fuel elsewhere or in situ.

The main purpose of pretreatment of the MSW is to improve the combustion process, by eliminating fractions of the waste which have a negative influence on the combustion behaviour of the waste.
For example kitchen and garden waste has a high moisture content which requires extra drying time in the oven, before ignition can take place. Furthermore this high moisture content varies enormously, which requires additional process control systems to maintain steady combustion conditions.

Stones and ceramics, but also glass and metals do not contribute to the combustion process; they are just heated up and then cooled down again. But still as they go through the oven they need to be transported over the grate and need to be handled in the bottom-ash treatment section. In so doing they are mixed up with the combustion residues of the other fractions - merely adding to the quantity of bottom-ash which contains all kinds of pollutants. Although they do not contribute to the combustion process they increase the amount of contaminated bottom-ash.

From this point of view it is obvious that separation of inert (stone, ceramics, etc.) and putrescibles offers a lot of benefits for the combustion process and the residues [Sommer et al, 1989]. Because of these benefits sometimes it is decided not to burn the waste completely but first produce a variety of RDF which is then burned directly or sold to be combusted elsewhere (e.g. in a cement kiln [Haley, 1990]). Sometimes RDF is co-fired with another fuel (e.g. light-oil [Arosio et al, 1990]).

Disadvantageous for the production and combustion of RDF is the problem of what to do with the remaining fraction. In theory most of it can be recycled or reused but in practice often the only option is landfill which can be a (too) big disadvantage. Especially because the remaining fraction has not been in the oven and therefore is not biologically inert, which is a disadvantage when landfilled.

Other problems often encountered are difficulties with the marketing and sales of produced RDF, if the RDF producing and the RDF combusting facility are not combined in one company on the same location. The sales of RDF can be very difficult, especially because in practice it appears to be very difficult to produce RDF with constant quality due to changes in the composition of MSW. Co-firing of RDF with another fuel often requires extra flue gas cleaning, which would not be necessary if the other fuel was combusted alone.

It appears to be very dependant on the situation, whether the production and use of RDF is an attractive solution or not.

In practice we see that RDF-technology has been used at some locations for quite some time and in some cases with success. However, it has not made a commercial break-through (yet).
On the other hand most modern combustors do not practice complete mass-burn either but perform some kind of treatment before the waste combustor: almost always metals and big parts are removed and the waste is diminished in size prior to combustion. This improves the homogeneity and thus the combustion behaviour of the waste [Kilgroe et al, 1990].

In the storage bunker where the waste is received (after magnetic separation and size-diminishing, if this is the case) the waste usually is mixed a couple of times (with the crane) to increase the homogeneity of the waste. The storage bunkers are designed with a capacity of several days of the waste combustion capacity in order to provide for a buffer in case the supply of waste is interrupted (weekends). An extra advantage of keeping the waste in the bunker for some time is the possibility to mix the waste and to let water evaporate making the waste a little dryer. This favours an easy ignition of the waste and it evens out differences in moisture content of the waste. (In day to day practice this effect is often negligable).

From the storage bunker the waste is fed to the combustor by a grab crane. Through a funnel the waste arrives at the dosage system. This can be continuous, using a 'continuous belt' grate as a first step, or discontinuous by using hydraulic rams, which shove the waste on to the grate. The continuous system seems to be better because it realises a more homogeneous feed rate. Nevertheless the rams are very often applied due to their better resistance to high temperatures. Also the waste does not fall on the grate but is shoved on it which means a lower chance of damaging the grate by big parts falling on it [Jochem, 1989].

2.2 Grate type, furnace geometry, combustion process

When the waste leaves the dosage system it enters the combustion chamber, where the waste is combusted.
Obviously the primary function of the combustion chamber is to mix air with the waste, combust as much of the waste as possible in a way which generates the least possible amount of pollutants. Furthermore the flows leaving the combustion chamber (i.e. bottom-ash and flue gas) should be optimally suited for further treatment or use.

For these purposes the combustion chamber contains three main tools: the grate, the furnace geometry and the process operation system which controls waste transporting speed and combustion air supply.

2.2.1 Grate type

A lot of grate types are used in the MSW combustors currently in operation: rotary drum grates, forward and reverse acting (reciprocating) grates, rocker grates, continuous (travelling) grates and others.
The main objectives of these grates are to:

- transport the waste, while it is burning, through the oven;
- mix the waste to improve the homogeneity;
- distribute the primary air (which is blown through the grate) over the waste.

And, of course, the grate must continue to fulfill its tasks for an acceptable period without maintenance or repair.

From the mentioned types of grates the forward and reverse acting reciprocating grates as well as the rotary drum grates are most frequently applied in modern combustors. The other grates (rocker grates, continuous grates, W-grates, drop-link grates, etc.) all have some disadvantages which lead to worse performances than the others on items like durability, air distribution, waste mixing, etc.
Figure 2 shows schematic pictures of the mentioned types which all three fulfil the objectives satisfactorily. Of course there still are differences between them.

Advantages of the rotary drum grate are the flexibility in transport speed of the waste and the relatively good durability of the grate bars. The main disadvantage is formed by the difficulties encountered with the primary air supply. Between the drums there are so-called 'scrapers' which make sure the waste is transported from one drum to another without too much waste falling through the grate. Through wear the openings between drum and scraper will get bigger and bigger which lowers the pressure drop for the primary air. So at first the primary air is supplied mainly through the rollers but after some time in operation more and more air will pass between the rollers, causing a bad air distribution. Furthermore less air through the roller means less cooling of the grate bars which can cause excessive wear. Also through fouling the openings between the bars can get blocked forcing more air to pass between in stead

of through the rotary drums.
The forward and reverse acting grates have a very good primary air distribution (also in the long term) but as they have more moving parts they have more mechanical wear and slightly shorter lifetimes than the rotary drum grate.
The reverse acting grate has very good mixing properties but is less flexible in transport speed of the waste. This is due to the fact that the transport speed is for a great deal determined by the slope of the grate which of course is fixed.
To improve the mixing capabilities of the forward acting grate sometimes the moving grate bars are not connected to one but to two driving systems. So when one moving grate bar is moving forward the next moveable grate bar is moving backward (figure 3).

2.2.2 Furnace geometry

The main function of the geometry is twofold:

- Distribution (through radiation as well as through convection) of the heat of the fire over the combustion chamber to ensure drying and ignition of the waste.
- Mixing of the combustible gases with air to ensure complete burn-out. The mixing needs to make sure that everywhere the oxygen level and the temperature is sufficiently high. Cold spots need to be prevented because in cold spots the reaction rates are much lower leading to emissions of CO and unburnt hydrocarbons.

Basically there are two types of geometries of the furnace: parallel flow and counterflow. A third type which is actually a mixture of these two is the intermediate-flow. Figure 4 gives an impression of these geometries.
The basis for the definition is the flow direction of the waste in relation to the flow direction of the flue gases.

The counterflow principle is very suitable for types of waste which are not easily ignited, due to a high moisture or a low volatile content (or both). The hot flue gases from the flame are led over the beginning of the grate before entering the boiler. The heat of the flue gases helps to dry and ignite the waste.

If the waste is not very moist and is easily ignited a parallel flow geometry can be applied [Scholz, Beckmann, 1991].

This offers the advantage that gases, originating from quick volatilisation at the beginning of the grate, are led through the flame and kept in the combustion chamber much longer causing a better burn-out of these gases. (In the counterflow design the burn-out of these gases mainly takes place in the first draft of the boiler.)

Another claimed [Reeck et al, 1991] advantage for the parallel flow design is that particles which are dragged along with the flue gases are lead back in the waste layer, which results in a lower concentration of fly-ash in the flue gases. Finally in parallel flow the bottom-ash is kept at a higher temperature until it falls into the ash-pit where the ash is quenched and thus rapidly cooled. The temperature range for the formation of PCDD/F out of organic fragments (Denovo-synthesis [Vogg, Stieglitz, 1986; Shaub, Tsang, 1983; Karasek, Dickson, 1987; Hagenmaier et al, 1987]) is very quickly passed in this way, which is claimed to result in a lower PCDD/F-content of

the bottom-ash [Hausschild, 1991].
A disadvantage for the parallel flow geometry is the bigger heat load in the combustion chamber especially when wastes with extremely high heating values (11-14 MJ/kg) are combusted. To prevent excessive wear due to high temperatures and fouling of surfaces through deposition of fly-ash particles extra measures (expensive protection materials) will have to be taken.

To ensure complete burn-out of the gases these need to be mixed with air (oxygen) very thoroughly. 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 temperatures 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.
The mixing is taken care of with two measures. First at the exit of the combustion chamber the geometry causes swirls and elevated velocities of the flue gas. Secondly the mixing is improved by the injection of secondary air at very high velocities (up to 100 m/s).

The first draft of the boiler has a bigger diameter than the combustion chamber exit, which lowers the speed of the flue gas and the design causes the gases to pass nearly in plug flow ensuring an even residence time distribution. Ideally at the exit of the combustion chamber the gases are fully mixed and a plug flow pattern in the boiler arranges for an even residence time of the gases at the desired high temperature. However, if through some deviation the mixing at the exit of the combustion chamber is not perfect, a plug flow design can not make up for this because in plug flow there is no mixing at all. That is why the gases do not pass in plug flow completely. On the other hand swirls will give rise to extra erosion and fly-ash deposits (see section 2.3.2).

The boiler is water-walled; this means in the walls there are water tubes in which water is heated and evaporated. However, in the first draft of the boiler the water tubes are shielded to minimise heat loss and keep the temperature of the gases above the required values.

Finally the furnace should be designed in such a way that there are no relatively cold areas. In these areas the reaction rates are slow, due to lower temperatures, which may result in incomplete combustion. Especially when there is a change in gas phase flow (different amount of flue gas, changed primary/secondary air ratio) this problem needs special attention.

2.2.3 Process control system

Solid fuels usually are characterised by an amount of volatile and an amount of so-called 'fixed carbon' (besides water and ashes). This indicates combustibles, which do not evaporate but burn on the surface of the remaining solids (bottom-ash).

On the grate the waste is burned in three stages: drying, devolatilization and combustion.

At first the waste is dried and is slowly heated up. The heat used for this is mainly supplied through radiation from the flame 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 and react with the supplied oxygen (mainly through primary air, in this stage).
On the last part of the grate the remaining solids are burned out.

Each of these three stages mentioned above require 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 change the ratio primary/secondary air. A normal (often used for design) air distribution [Becker et al,1991/92] is 40% secondary air and 60% primary air which is divided over the three stages at a ratio of 10:40:10.
Also the speed of the grate per zone is variable.

Even with the ability to vary the grate speed and the air supply good operation of an MSW combustor is very complicated and depends on many influences.

The main challenge with the control of the combustion is caused by 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 there are other indicators which have to inform the control system on e.g. an increase in the heat content of the waste or the need for more air on a certain spot.
Just until a few years ago the main indicator was the steam production rate: if the production decreases more waste is fed to the grate and if the production increases less waste is supplied. The supply of air was then varied along with it. Sometimes the temperature of the rear-wall was used to determine the grate speed: if the temperature got too high it meant that the fire moved to 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 not very accurate or quick, resulting in unstable fires and high emissions of CO, NO_x and unburnt organic compounds (precursors for PCDD/F).

Today modern combustors at least monitor carbon monoxide, oxygen, air flow and temperature, apart from steam production rate. Some systems go further and use techniques like infrared monitoring of waste layer temperatures [Schumacher, Schäfers, 1991] or of water- and CO-concentration above the layer by pyro-indicators [Hausschild, 1991]. By measuring the temperatures, the waste feed and transport rate can be adjusted to keep the fire on the desired place on the grate. The supply of primary air also is based on this information.
Pyro-indicators measure water in the beginning of the grate to establish the moisture content of the waste. As this is the component in the waste which changes the most rapidly the moisture content gives good information on fluctuations in the heating value of the waste. This information then is used for the supply of primary air.
In the middle of the combustion chamber the CO-content is measured to give information for the supply of secondary air, and in 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 means 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 but more important is improving the mixing of the flue gases.
These techniques (infrared monitoring/pyro-indicators) are very new and only applied in very few installations [Hausschild,1991;Schumacher,Schäfers,1991], sofar with good results as to combustion completeness.

2.2.3.1 Air supply

The supply of air is very important to the overall performance of the combustor. As stated before the first objective of waste combustion is to dispose of the waste safely with the least possible emission of pollutants. Secondly a maximum amount of energy should be recovered out of this process.
With respect to the first objective 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 [Schumacher, Schäfers, 1991; Schäfers, 1991; Albert, 1991a; Martin, Zahlten, 1989; Sierig, 1989], but not unlimited. Below excess air levels of 1.3-1.4 the CO-emissions increases again. To keep the CO-(and the unburned hydrocarbon) emission low, when combusting with less air, the flue gases should be very well mixed (secondary air, furnace geometry).
The extra supply of oxygen through the secondary air can give rise to higher NO_x-emissions, if the temperature (locally) is very high (>1100-1200 °C). To prevent this, flue gases can be injected instead of air: less oxygen, same mixing impact. This is currently under investigation. The main problem with this method is corrosion in the flue gas recycling system [Albert, 1991a].
When energy recovery is considered (second objective), an increase in the amount of flue gas causes a decrease in the energy efficiency of the boiler. More flue gas means lower temperatures at the inlet, slower heat-exchange (larger contact surface required) and a bigger heat-loss in the chimney.
Apart from that the size of the boiler and the flue gas cleaning system also increases when the flue gas flow increases.

All together it is obvious that the amount of combustion air should be minimized to the point below which through lack of oxygen CO and hydrocarbons are not completely burned any more and it cannot be solved by increasing the mixing intensity. The geometry thereby is a very important factor because it determines for a great deal how good the mixing can be.
In practice nowadays this means that modern combustors are working with excess air ratios of 1.6-1.8. Older combustors usually operate with ratios like 1.9 to 2.5.

The distribution of the air depends on the process control system. In the earlier days the total amount of air was kept constant and only the division between primary and secondary air was adjustable. If more heat generation was required (more steam production) more air was supplied through the grate and less air secondarily. 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 water content of the gas phase in the beginning of the grate), the air ratio and distribution is adjusted to the obtained information. A slight increase in heating value (less water, more volatilization in the beginning of the grate) means a little increase in

primary air supply to the beginning of the grate, to supply enough oxygen. If the heating value increases further less primary air is supplied to the beginning of the grate, to prevent locally high temperatures and high NO_x-forming. Then the secondary air is used to supply the required oxygen and ensure the burn-out of the gases. If at high heating values all the air is supplied through the grate (and thus all the combustibles are combusted on the grate) the temperature would get too high and the grate would be damaged. 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 [Wijdeven, 1991]. Thus the combustion on the grate is incomplete and the heat load on the grate is lower. Completion of the combustion then has to be realised with the secondary air. If a low amount of primary air is applied, the burn-out of the bottom-ash requires special attention.

All this indicates that good operation of a combustor is complicated and dependant on many influences.

2.2.3.2 Raw flue gas concentrations

The emissions of HCl, HF and SO_2 cannot be influenced by the way an combustor is designed or operated: this is determined by the concentration of Cl-, F- and S-compounds in the waste. An exception must be made for the dosage of Ca-compounds to the waste prior to combustion. These compounds fixate part of the S, Cl and F in the bottom-ash, reducing the flue gas emissions of these components [Scholz, Beckmann, 1991]. However, this decreases the quality of the bottom-ash considerably.

The particulate matter emission is slightly influenced by the amount of primary air and the way and the speed at which this primary air is blown through the grate: higher speeds will cause more particle entrainment.

Emissions of NO_x, CO, unburned hydrocarbons and PCDD/F are determined by the conjunction of a lot of parameters like geometry, process control, air supply and air distribution. NO_x is of course also partly determined by the N-content of the waste.

Average emission levels which have been proven possible in general (no extremes) in modern combustors without further treatment are given in Table 2.1.

Table 2.1 Emission levels attainable through primary (in the combustion process) measures, in modern combustors (no extremes)

Component		Level	References
CO	[mg/Nm³]	10-30	Jochem, 1989 Schumacher, Schäfers, 1991 Abassi, Khinks, 1991
NO_x	[mg/Nm³]	200-350	Reeck et al, 1991 Albert, 1991a Haji Javad, 1991
TOC	[mg/Nm³]	< 1	Reeck et al, 1991 Albert, 1991a
PCDD/F	[ng I-TEQ/Nm³]	1-8	Lindbauer et al, 1991
Burn-out bottom-ash	[wt%-C]	1-2	Reeck et al, 1991 Albert, 1991a Martin, Zahlten, 1989

From the references it becomes clear that the grate type has no significant influence on these performances as long as the grate allows for a good air distribution and process control.
Also the furnace geometry (parallel flow, counterflow or intermediate-flow) does on itself form no restriction to reach the levels as in Table 2.1.
([Jochem, 1989; Schumacher, Schäfers, 1991; Albert, 1991a] consider a forward acting grate with counter- or intermediate-flow, [Reeck et al,1991] a rotary drum grate with parallel flow, [Martin, Zahlten, 1989] a reverse acting grate with counterflow).
For each of these grates and geometries special measures can be taken to reach the desired performances.
The decision which grate or geometry is to be applied depends on other parameters like durability, costs and waste characteristics.

2.3 Boiler

A further object of MSW combustion is to recover as much energy as possible from the waste. This recovering is done in a boiler where the flue gases are cooled from temperatures of 900-1200 °C to 200-250 °C. At first heat is transferred via radiation and later through convection.

There are different ways to recover the energy (steam, hot water, direct drying). The most flexible way is to produce steam which is used for electricity generation, with or without usage of the remaining heat. Therefore only this situation is considered here.

The heat that is withdrawn from the flue gases is used to evaporate and superheat water. The produced steam then is fed to a generator which produces electricity. The outlet of the generator still contains energy which can be used for district or process heating. The use of the energy is very dependant on the local situation: if there is no direct use for the heat the electricity generation will be maximised. The remaining heat content of the steam is not used and the total energy recovery efficiency is (at normal steam parameters: 40 bar, 400 °C) limited to around 22%. The combination of electricity generation with delivery of heat to industry (distillation of water, heating up process flows) or domestic urban consumers offers a higher efficiency (up to 80%) and should therefore be preferred. If a combination with district heating is made there have to be provisions to take care of the heat in summertime, when the demand for heat from the district is very low. Of course this decreases the efficiency of the system unless the heat can be stacked away until it is needed. This last option is difficult and several studies are dedicated to this topic at the moment.

2.3.1 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.
As figure 5 shows, the difference between these two types is given in the way the heat transfer pipes are oriented in the second part of the boiler.
The first part is the same for both type of boilers. In this part heat is transferred through radiation which means that there are no (water)tubes in the gas stream but only in the walls (empty drafts). In the beginning of the radiation part these water-piped walls are shielded to make sure the temperature does not drop too quickly. As already mentioned the flue gases need a residence time of at least 2 seconds at temperatures above 850 °C. The first part of the boiler supplies the space for this residence time.
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 they enter the convective part [Pröfrock, Thalmann, 1991]. In the convective part tubes, containing water or steam, are placed in the flue gas stream perpendicular to the flow direction. In a vertical boiler this means they are oriented horizontal, whereas in a horizontal boiler the tubes are oriented vertical. The flue gases flow around the tubes transferring heat to the tubes and indirectly to the water or steam in the tubes.
In the convective part the flue gases are generally cooled to 200-250 °C, before leaving the boiler.

The main advantage of the horizontal versus the vertical boiler is given by the cleaning system of the convective tubes. 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 2.3.2).
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. Through 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, because the particles are lying on the tubes and are not easily removed through vibration of the tubes. 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 into the boiler between the tubes to remove the dust on the tubes. The costs related to the usage of steam is one big

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 is done through erosion.

The above described advantages in fouling and cleaning give the horizontal boiler a slightly prolonged lifetime and lower cleaning costs in comparison with the vertical boiler. Regarding investment costs and space occupation the vertical boiler is preferable.
Both boiler types are known to reach uninterrupted operation times of 8000 hours at availabilities of 80-85% and there are no really decisive differences between the two. Often the decision has to be made on local demands like the availability of space or height, especially with extensions or retrofits of existing installations. When these demands are not present the horizontal boiler is more often applied than the vertical one.

2.3.2 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 [Veabrin, 1990]. In MSW combustors these parameters usually are kept far below that 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 [Veabrin, 1990; Barniske, 1990; Ganapathy, 1991]. Below these temperatures the main cause of corrosion is CO in combination with HCl. Through oxidation of the tube material a protective layer of metal-oxides is formed. CO reduces these oxides after which Cl-corrosion of the metal takes place rapidly. The two main concerns to prevent corrosion thus are to keep the tube surface temperature close to or below 400 °C and to ensure a good gas burn-out (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 to provide with extra mixing; to enable CO and unburnt particles to meet oxygen and react [Pröfrock,Thalmann,1991].
- The superheater tubes are placed in co-current flow with the flue gas stream because this keeps the tube surface temperature lower than in counter-current flow [Pröfrock,Thalmann,1991].

The second concern, low CO, is first of all realised through good combustion practices as described in chapter 2.2.

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.
Finally if the flow pattern of the flue gases changes or if the furnace is not well designed a piling up of fly-ash can occur in corners or on walls, with the above mentioned consequences.

At low flue gas temperatures another type of corrosion can take place: dew-point corrosion. This means that the temperature has dropped so far that acidic liquids condensate on the tubes. Normally spoken this is no problem if the tube surface temperature is kept above 180 °C.

Besides corrosion also erosion can take place, especially if soot-blowing is applied without care. Damage can be severe because erosion takes of the protecting oxide layer after which corrosion takes place. Carefully installing the soot-blowers (if any) and lowering the flue gas velocity (<7 m/s) usually solves these problems. Special attention is always needed for turns and corners where local velocities can be higher.

In general, boilers in MSW combustors are designed with steam parameters of 40-45 bar and 400-450 °C [Pröfrock,Thalmann,1991;Barniske,1990]. 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 6. This figure gives an approximate correlation and is based on operational data from German combustors [Barniske, 1990].

There are MSW combustors that apply steam temperatures above 450 °C but these combustors need sophisticated (and expensive) tube materials [Pfeiffer, 1991] and careful operation (low CO and particulate matter). Another possibility is to produce steam at temperatures below 400 °C in the boiler connected to the waste combustor, and heat up this steam further with fossil fuels (or possibly with other fuels like biogas) in a separate installation [Ganapathy, 1991; Pfeiffer, 1991; Albert, 1991b]. Economics will have to decide whether this is suitable or not.

2.4 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 for a modern combustor is given in Table 2.2.

Table 2.2 Typical composition of raw flue gas (before cleaning) [Jochem, 1989; Reeck et al 1991; Schumacher, Schäfers, 1991; Albert, 1991a; Martin, Zahlten, 1989; Abbasi, Khinkis, 1991; Haji Javad, 1991; Lindbauer et al,1991]
All values in mg/m^3 dry gas at stp and 11 vol% O$_2$

Component	Raw flue gas concentration		Dutch guideline	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	2)
TOC (as C)	1	20	10	50 2)
Heavy metals:				
- Hg	0.1	1	0.05	95
- Cd	0.1	0.5	0.05	90
- others	1	5	1	80
PCDD/F [ng TEQ/m^3] 3)	1	10	0.1	99

1) The removal efficiency required to comply the maximum value with the Dutch guideline 'Richtlijn Verbranden 1989' (explanation of guideline in chapter 3.4).
2) Not taken care of in flue gas cleaning system (see text).
3) TEQ = Toxicity Equivalent Quantity (related to 1,2,7,8-TCDD).

The required removal efficiencies clearly demonstrate the considerable challenge which faces the flue gas cleaning system for the different components.
With the exception of CO and TOC (Total Organic Carbon) every component is taken care of in most of the modern flue gas cleaning system. For CO and TOC there usually are no cleaning techniques applied, which means that at the exit of the boiler the CO-concentration must be within the limits.
Only an 'oversized' SCR installation might through catalytic oxidation reduce the amount of CO and TOC in the flue gases (see section 2.4.4.2).

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 (2.4.1), acid gases (2.4.2), NO$_x$ (2.4.3), dioxins and furans (2.4.4) and heavy metals (2.4.5).

2.4.1 Particulates/dust

Almost always the first step in a flue gas cleaning system is the removal of as much dust as possible. This is done for two reasons. First of all dust has a negative influence on the functioning of the other flue gas cleaning equipment: the more dust is removed up front the better the operation of the rest of the flue gas cleaning.

Secondly the possibilities for reuse of fly-ash are larger 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.

A relatively simple (and cheap) technique is the use of a cyclone or a multi-cyclone (several small cyclones in parallel connection). However, the removal efficiency of a cyclone is rather low (80-85%) and especially small particles (< 10 μm) are not removed.

A more sophisticated technique is the use of an electrostatic precipitator (ESP). This apparatus is 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 [Haji Javad, 1991].

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 [Vogg, Stieglitz, 1986; Shaub, Tsang, 1983; Karasek, Dickson, 1987; Hagenmaier et al, 1987; Vogg, Merz, 1990]). For this reason the temperature should be kept at 180-220 °C.

An even better removal efficiency (> 99.9%) can be realised by using a fabric filter (= bag filter or bag house). This apparatus, however, is relatively expensive and causes a relatively large pressure drop (bigger air compressor, more energy use). Another disadvantage is the need for an accurate temperature control of the fabric filter: to protect the fabric of the filter the temperature has to be below 180-200 °C but above the dew point of the gases. Fabric filters need to be applied in parallel sequences to be able to continue operation if one unit is out of order (maintenance, rupture of the fabric, etc.). Because of its high removal efficiency and the need to remove as much fly-ash as possible before further cleaning, the fabric filters are more and more applied.

Together with the dust some more components are removed, like heavy metals and PCDD/F (see chapter 2.5.2). This is strongly dependant on the temperature of the flue gas (condensation of gaseous heavy metal compounds) at which the dust is removed.

If after this separation the dust concentration does not conform to the regulations this does not have to be a problem. A lot of the remaining particulates is caught in the following equipment (scrubber, active cokes filter).

2.4.2 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 three use an ad- or absorbent which is sprayed in the flue gas stream.

2.4.2.1 Dry scrubber

The dry technique uses a dry powder to adsorb the acid gases. This powder usually is a calcium hydroxide powder with a large surface (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 strong advantage over an ESP firstly because of the higher removal efficiency but also because on the filter a layer of the partly used adsorbent builds up, providing an extra opportunity to adsorb pollutants. Thus the usage of adsorbent is less for the combination of a dry scrubber with a fabric filter compared to the combination of a dry scrubber with an ESP. 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.
Figure 7 displays a block scheme of a dry flue gas cleaning system.

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) [Semmler, Weyer, 1992; Reimann, 1991a] is required to adsorb enough acid gases to comply with the regulations. This not only means high costs because of the usage of relatively large amounts of adsorbent, but also the amount of residues is relatively large: 25-45 kg residue per Mg MSW combusted [Semmler, Weyer, 1992; Barniske, 1989; Göttlicher, Anton, 1990]. Sofar there are no possibilities for reuse or recycling of these residues, which means they have to be landfilled, usually as chemical waste (high costs).
A dry scrubber is easy in operation and requires relatively small investments.

Besides removing acid gases the dry scrubbing technique is capable of removing part of the remaining dust (ESP or fabric filter), heavy metals and PCDD/F, especially when besides calciumhydroxide active cokes is injected too [Kempin, 1991]. Without special measures and large usage of adsorbent this will, however, not be enough to reach emission levels conform the emission regulations like the ones in Germany, Austria or the Netherlands.

2.4.2.2 Semi-dry scrubber

In a semi-dry scrubber not a powder but a solution or suspension (of calciumhydroxide or -carbonate) 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 8 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) [Semmler, Weyer, 1992; Reimann, 1991a], so the costs related to the usage are less. Evidently also the resulting amount of residue is less then with dry scrubbing: 15-35 kg per Mg MSW combusted [Semmler, Weyer, 1992; Barniske, 1989; Göttlicher, Anton, 1990]. Like the residue from dry scrubbing the residue from semi-dry scrubbing cannot be reused or recycled and has to be landfilled as chemical waste. Like the residue from dry scrubbing the residue from semi-dry scrubbing is not easily reused or recycled and often has to be landfilled as chemical waste (see section 2.5.3).

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 for the dry scrubber and in some cases if active cokes is injected also, the strictest regulations can be met [Matthes, 1991; Morun et al, 1991].

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

2.4.2.3 Wet scrubber

Wet scrubbers also use a liquid absorbent but in contrary to the other two systems the residue also is a liquid. Modern wet cleaning systems are multi-staged: first an acid stage and secondly a basic or neutral stage.
In the acid stage water (acidic because of recycling) 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.
SO_2 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 caliumhydroxide solution in the scrubber.
Figure 9 shows the block scheme for 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) [Semmler, Weyer, 1992]. The resulting waste water can be treated, cleaned and disposed of in the sewer 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 10). The resulting solid residue amounts to 10-15 kg per Mg MSW combusted [Semmler, Weyer, 1992; Barniske, 1989]. 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 chemical waste. However, more and more permits demand a waste water free operation 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) is added to the second stage of the

scrubber, resulting in higher absorption of Hg [Reeck et al,1991].
PCDD/F is not captured in a wet scrubber, except for the PCDD/F which is adsorbed to particles or droplets. At the time experiments with the addition of active cokes to the washing water of a wet scrubber are being executed to find out whether this increases the absorption of Hg and PCDD/F.

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

2.4.3 NO_x

The NO_x-emission can be controlled by primary and secondary measures. Primary measures are meant to minimise the formation of NO_x out of fuel-bound or atmospheric nitrogen. These measures are taken in the combustion chamber as described in chapter 2.2.3. The two main ways, of which the first is the most important, to keep NO_x-concentrations low are:

- 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 [Abbasi, Khinkis, 1991]). This is done by dividing the combustion air over primary and secondary air in a careful controlled way and by using recycled flue gases as (part of the) secondary air.
- Prevent the formation of thermal-NO_x (NO_x from reaction of atmospheric nitrogen with oxygen) by keeping the temperature below ca. 1200 °C, not just average but also locally (prevent hot spots). This is done by good mixing and dependant on a good design of combustion chamber and furnace.

A third possibility which has been developed the last few years is recirculation of the flue gas as combustion air.

With these primary measures NO_x-concentrations of 250-350 mg/Nm^3 in uncleaned flue gas can be reached (table 2.1).
Because some emission regulations require that the NO_x-emission is cut back to 200 or even 70 mg/Nm^3 secondary measures are also needed.
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 on active cokes.

Besides these technologies also chemical adsorption with sodiumperchloride (not successful yet [Reeck et al, 1991]) or reaction with hydrogenperoxide (pilot-plant scale) seems to be possible in theory.

2.4.3.1 SNCR

In the furnace a solution of ammonia or an ammonia-forming compound (e.g. urea) is sprayed in the flue gases, usually in two or three stages. At temperatures of 900-1050 °C the ammonia reacts with NO_x to N_2 and water [Lyon, 1987]. The injection has to be very well placed because the temperature range in which the reaction runs well is very narrow. Usually a stoichiometric ratio (NH_3 over NO_x) of

2-4 is applied which leaves an ammonia emission, which has to be taken care of (stripping and recycling of the NH_3) [Krager, Schulz, 1990].
At these stoichiometric ratios NO_x-emission reductions of 60-80% are claimed to be possible with SNCR [Haji Javad, 1991; Semmler, Weyer, 1992].
The investment costs of SNCR are low. The major disadvantage is the ammonia-slip which needs 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 [Krager, Schulz, 1990]. Emission levels of 70 mg/Nm^3 (with acceptable ammonia-slip) are only reached with SNCR with consideralble effort [Thomé, 1991].

2.4.3.2 SCR

With an SCR-DeNOx process the same reactions occur as with SNCR. Only thanks to the use of a catalyst the temperature at which these reactions occur are much lower (200-300 °C). In the flue gas cleaning sequence there are several places where the SCR could be placed but with MSW combustion it is usually situated after the scrubbers. This is to prevent the catalyst from being poisoned with particulates.
The SCR-process uses a near stoichiometric amount of ammonia causing very low ammonia emissions (< 5 ppm by volume possible [Thomé, 1991]). An NO_x-emission reduction of 90% can be reached [Semmler, Weyer, 1992]. Disadvantages are formed by the costs caused by the usage of catalyst and the need to heat up the flue gases to the desired reaction temperatures. Furthermore SCR requires considerable investment.

An extra advantage of the SCR technology is the possibility to combine the reduction of NO_x with a reduction in PCDD/F-emission (see chapter 2.4.4.2).

2.4.3.3 Adsorption on active cokes

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 nearstoichiometric amount of ammonia, but sofar only reaches NO_x-emission reductions of around 60% [Semmler, Weyer, 1992], which might not be enough to reach a limit of 70 mg/Nm^3.

2.4.4 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 (prevention de-novo-synthesis [Vogg, Stieglitz, 1986; Shaub, Tsang, 1983; Karasek, Dickson, 1987; Hagenmaier et al, 1987; Vogg, Merz, 1990]) and high temperature dust removal (removing the catalyst for the de-novo-synthesis). The extent to which these measures are effective is not clear yet.
Secondly there are two ways to remove PCDD/F once they have been formed:

- adsorption on active cokes;
- catalytic oxidation.

2.4.4.1 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 cokes together with calcium hydroxide in the flue gas stream just before a fabric filter (German: 'Flug- stromadsorber') or together with the other ad- or absorbent in a dry or semi-dry scrubber. As already mentioned at the moment experiments are executed with the addition of active cokes to the washing water of a wet scrubber. Secondly instead of simply injecting the cokes in the flue gas stream, a circulating fluid bed can be used. In this fluid bed the cokes is being fluidized by the flue gas. The cokes that is dragged along with the flue gas is separated in a fabric filter and fed back to the circulating fluid bed, keeping the usage of the active cokes very low. The third technique in which adsorption to active cokes can be realised is a fixed bed of cokes. This fixed bed, however, is not entirely fixed, because 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 of capturing very efficiently almost every pollutant: not only PCDD/F but also other hydrocarbons (e.g. PCBs, 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 check.

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 2.5.4).

In table 2.3 (taken from [Semmler, Weyer, 1992]) a comparison is made between the different active cokes techniques.

Table 2.3 Comparison between three different flue gas cleaning techniques based on adsorption to active cokes [Semmler, Weyer, 1992]

Parameter	Fixed bed	'Flugstrom-adsorber'	Circulating fluid bed
Investment costs [%]	100	55	66
Cokes usage [kg/Mg 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 'Flugstromadsorber' and 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 an 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 2.5.4).

2.4.4.2 Catalytic oxidation

Instead of adsorbing PCDD/F on cokes they can be destroyed through catalytic oxidation. It appears that the same catalyst which causes the reduction of NO_x also oxidizes PCDD/F to CO_2, HCl and water. Also NH_3 is oxidized to N_2 and water [Semmler, Weyer, 1992; Thomé, 1991]. This means that if the SCR is oversized higher stoichiometric ratios can be used, realising higher NO_x-emission reductions. And still the last part of the SCR can be used to destroy PCDD/F, but for this to happen first all NH_3 has to be oxidized. Besides PCDD/F also unburnt hydrocarbons (TOC) and CO are oxidized [Fahlenkamp et al, 1991; Anonymus, 1991].

However, it is absolutely necessary that the flue gas is cleaned from acid gases and dust prior to entering the SCR-equipment. As mentioned before dust poisons the catalyst and acid gases form corrosive agents in the presence of ammonia (ammoniumchloride, ammoniumsulfate).

2.4.5 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 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 [Reimann, 1989]. By using additives such as TMT15 in the second stage of the scrubber or by using active cokes adsorption, the concentration of these metals in the flue gas can be reduced below the required amounts.

2.5 Residue treatment

As stated before the main objective of waste combustion is to dispose of the waste safely with the least possible emission of pollutants.
Waste combustion causes several outgoing flows. First of all the flue gas stream which has been treated in the foregoing sections. In general per tonne of MSW combusted 5000-5500 Nm^3 of flue gas are formed, depending on the amount of excess air [Reimann, 1989; Reimann, 1992].
Besides flue gas several solid and liquid residue streams can leave the MSW combustor:

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

In the next sections each residue stream will be discussed.

2.5.1 Bottom-ash

MSW combustion usually results in 250-350 kg per Mg MSW combusted [Barniske, 1989; Göttlicher, Anton, 1990; Reimann, 1989; Faulstich, 1991].
The bottom-ash falls from the grate into the handling system where the bottom-ash is quenched using around 0.35 m^3 of water per Mg MSW combusted [Reimann, 1989]. After this almost always the bottom-ash is crushed and through magnetic separation the iron is removed and reused. The remaining bottom-ash can be reused under certain conditions in construction materials for roads and buildings.

To allow for reuse in construction materials (or lately even for normal landfill -not as toxic waste- in some countries) there are several demands on the composition which differ considerably from country to country. Mainly the content of unburnt material and of water-solubles is restricted. Lately these demands become more and more stringent requiring either more treatment of the bottom-ash, improved combustion techniques or even a limited waste acceptance policy.

If the bottom-ash does not meet the demands for reuse after crushing and removing the iron, washing and/or melting has to be applied, or else the bottom-ash is to be landfilled as chemical waste. By washing the bottom-ash the water soluble parts can be removed. Sometimes the acidic and basic washing water of the wet scrubber is used for this (MR-process [Stubenvoll, 1989]). Melting does not remove the solubles but transforms the bottom-ash in a glass 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 [Jochem et al, 1991], but similar processes are developed/under development by Babcock [Schleger, 1991] and Lurgi [Lurgi, 1990]). Disadvantages of these processes are the relatively high investment and energy costs. Above this there still are some unsolved problems like CO-formation above the melt (explosion risk) and corrosion and low durability of the electrodes (used for melting), which prohibit large scale application of this technique even today.

The costs of disposal of the bottom-ash can have a large impact on the economics of an MSW combustor due to the large amount of bottom-ash produced. Therefore a lot of research focuses on 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.

2.5.2 Fly-ash

Per tonne of MSW combusted around 20-40 kg of fly-ash is produced (presuming the fly-ash is separately removed, not together with the scrubber residues) [Barniske, 1989; Göttlicher, Anton, 1990; Reimann, 1989; Faulstich, 1991].
Fly-ash cannot be reused or landfilled without further treatment, because of the high content of pollutants like heavy metals and organic matter (among which PCDD/F: 1-10 mg/kg [Reimann,1992;Schleger,1991]), which are easily leached out. Furthermore fly-ash is easily blown away and spread by the wind if no measures are taken. At least the fly-ash has to be fixated with cement or stacked in big bags to improve handling and leaching behaviour. At this time most of the fly-ash is treated like this and then landfilled, only a small fraction of it is used in road and construction works.

However, the amount of pollutants is too high to meet most regulations (some of which will come into effect soon) to be reused or landfilled. 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 be implemented with the melting of the bottom-ash and offers the advantage by doing this any PCDD/F or other organic material contained by the fly-ash is destroyed. If the bottom-ash is melted this usually is the best way to dispose of the fly-ash. For fly-ash only other processes are of interest because of less use of energy and possibly better feasibility (melting not fully developed, see 2.5.1): low temperature destruction of PCDD/F [Hagenmaier, 1988] and the 3R-process [Vehlow et al, 1989]. The first process has been demonstrated on pilot-plant scale

[Stützle et al, 1991], 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 great extent. The fly-ash then is dried, mixed with binder, pelletized and led back on the grate of the combustor, where PCDD/F and other organic matter is destroyed.

2.5.3 Scrubber residues

Residues of dry and semi-dry scrubbers mainly consist of salts. Dry scrubbers produce approximately 25-45 kg residue per Mg MSW combusted [Semmler, Weyer, 1992; Barniske, 1989; Göttlicher, Anton, 1990], whereas semi-dry scrubbing results in 15-35 kg per Mg MSW combusted [Semmler, Weyer, 1992; Barniske, 1989; Göttlicher, Anton, 1990]. Sofar there are no possibilities for reuse or recycling of these residues, which means they have to be landfilled, usually as chemical waste (high costs). Before landfilling they usually are stacked in big bags or fixated with cement or binder.

The waste water of a wet scrubber can be evaporated resulting in 10-15 kg per Mg MSW combusted [Semmler, Weyer, 1992; Barniske, 1989]. This can be done implemented in the flue gas cleaning system or separately (see figures 9 and 10). Naturally implementation means the residues are mixed up with other flue gas cleaning residues, whereas separate treatment means the residues can be collected and disposed of apart from each other. Either way the treatment is the same as for the (semi-)dry scrubber residues: stacking in big bags or fixation and subsequent landfill.

However, there are other ways to treat the waste water of the scrubber 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 (because of recycling of the wash water) 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 fixated). Other waste water streams can also be used in the quench.
   The HCl-solution is distilled towards concentrated HCl (30-31 wt% solution) which can be sold commercially [Thomé, 1991; Faulstich et al,1991]. Around 16.1 kg of concentrated HCl per tonne MSW can be produced like this [Thomé, 1991]. The residues from the distillation are landfilled together with the residue from the quench.
   Instead of distillation the HCl-solution could also be neutralised with $Ca(OH)_2$ or NaOH which renders solids which can be separated. The remaining solution is evaporated. The first additive renders solid $CaCl_2$ but this has little to no use because the production of $CaCl_2$ in other branches (mainly soda production) already exceeds demand. The second renders solid NaCl (common salt) (10-20 kg/tonnes MSW [Göttlicher, Anton, 1990]) which can be used in the chlorine-alkali-electrolysis process, which produces NaOH again and Cl_2-gas. As the need (of the industry) for NaOH exceeds the need for Cl_2 there is an excess of Cl_2-production already. As a consequence this route is useless if there is no 'new' use for the Cl_2-gas because then this has to be burned to HCl again [Thomé, 1991;

Faulstich et al, 1991; Enders et al, 1991]. However, this process has been realised at two combustors in Germany: Stapelfeld and Iserlohn [Faulstich et al, 1991]. 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 $Ca(OH)_2$-solution is used, a $CaCl_2$-solution is formed through absorption of HCl (10-20 kg per tonne MSW [Göttlicher, Anton,1990]). This $CaCl_2$-solution can be treated with sulphuric acid resulting in a HCl-solution (distillation and sale) and solid Ca SO_4 (* 2 aq: gypsum) after washing and dewatering. 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 [Faulstich et al, 1991].
c. If in the first step the HCl is removed, then the second step can be washed with $Ca(OH)_2$. This absorbs the SO_2 which results in Ca SO_4 (* 2 aq: gypsum) after washing and dewatering [Thomé, 1991; Faulstich et al, 1990]. In fossil fuel fired power station this technique is well established, making the marketing and sales of the (over)produced gypsum difficult. Especially because the quality of the gypsum produced like this in fossil fuel fired plants is better than the gypsum from MSW combustion plants (heavy metal content).

2.5.4 Contaminated active cokes

In table 2.3 it has already been stated that depending on the technique 0.3 to 3.6 kg active cokes per tonne MSW is used [Semmler, Weyer, 1992]. As this active cokes adsorbs almost every pollutant present in the flue gases (very useful in flue gas cleaning) the used active cokes is thus contaminated with all kinds of pollutants: organic matter (among which PCDD/F, PCB, etc.), but also HCl, SO_2, dust and heavy metals. What to do with this active cokes is not really known if the state-of-the-art is considered. Several options are being suggested but as there are at the time only 7 MSW combustors in operation in Europe which have active cokes adsorption implemented in their flue gas cleaning technique there is no established solution yet.

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) [VDI, 1992] or in a separate combustor. Both routes are not without problems.

When the cokes is fed back to the combustor special care has to be taken that the cokes particles, which are small (1-4 mm in diameter), do not fall through the grate and are not entrained with the flue gas flow without being completely burned. The first problem might not be so big if the fall-through of the grate is recycled and fed back on the grate. The second, however, can give big 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 (locally) high CO-levels: see section 2.3.2). In order to diminish the entrainment the used cokes can be pelletized before feeding to the grate. Whether this really is a solution is questionable, because while burning 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 give more problems than it solves.

Separate combustion of the cokes of course has the disadvantage of extra investments. On the other hand this offers the possibility to design the apparatus especially for the combustion of cokes. Furthermore the installation does not have to be big and process control probably is a lot easier compared to a large MSW combustor, making the risk for calamities a lot smaller.

At the time the combustion of active cokes in a cyclone burner, a circulating or entrained 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 wastes (chemical or clinical wastes) as fuel can be made.

No experiences on any of these processes are available yet. At present active cokes is combusted in rotary kilns, designed for chemical waste combustion.

2.6 Conclusion state-of-the-art system

In this paragraph chapters 2.1 to 2.5 are summarized by describing a state-of-the-art system. This is not the only sensible system possible, but it is one commonly accepted sensible system.

This description assumes mass-burn with energy recovery through steam production.

2.6.1 Pretreatment of MSW

The MSW is received in a bunker with a capacity of several days combustion capacity. Before it is fed to the combustor the big parts are removed and/ or diminished in size. If possible the waste is mixed while it is stored in the bunker. The waste is fed through a funnel and arrives via a dosage system consisting of two hydraulic rams on the grate.

2.6.2 Grate type, furnace geometry, process control

The grate is either a forward or a reverse acting reciprocating grate and consists of several zones, each of which can be controlled separately (speed and air supply). In principle a rotary drum grate is also very possible but the forward and reverse acting grates are preferred because of the better air distribution. Besides that the roller grate is only manufactured by one or two companies whereas there are more than 7 companies who manufacture a forward or a reverse acting grate.
The furnace is built in counterflow geometry. An intermediate flow or a parallel flow geometry is also possible. However, as it is expected (chapter 5) that the heating value of the MSW will rise in future, problems with the furnace load are expected if a parallel flow geometry is used in combination with a forward or a reverse acting grate. So far only combinations of a parallel flow geometry with a rotary drum grate are

known.
Because the forward and reverse acting grates are preferred also the counterflow geometry is preferred here.

A great part (ca. 40%) of the required combustion air is supplied through secondary air injectors. The total excess air ratio is 1.6-1.8. Experiments to decrease the excess air ratio using flue gas recycling are under execution at the moment.

The process is controlled by monitoring temperature, carbon monoxide and oxygen level, and all the flows including the steam production rate. The air supply to each zone of the grate can be varied as well as the ratio primary and secondary air. The supply is correlated to the monitored parameters. The primary air is preheated to 120-140 °C.

2.6.3 Boiler

A horizontal boiler is applied with (depending on the size of the boiler and the velocity of the flue gases) one, two or three empty drafts (radiation part) before the horizontal convective part. In this study the horizontal boiler is preferred over the vertical boiler due to the easier and cheaper cleaning of the convective tubes and the subsequent slightly longer lifetimes.

In the beginning of the radiation part the water tubes (in the walls) are shielded to keep the flue gas temperature at the required level for the required time. In the radiation part the flue gases are cooled to 600-700 °C, and in the convective part the temperature of the flue gases is further reduced to 200-250 °C. The tubes in the convective part are cleaned by automatic mechanical knocking systems.

Steam temperature is limited to around 400-450 °C due to increased corrosion problems at higher temperatures. If higher temperatures are required the steam can be heated up further outside the MSW combustor system with fossil (or other 'clean') fuels. To minimize erosion the flue gas velocity is kept below 5-7 m/s.

2.6.4 Flue gas cleaning system

The strictest emission guidelines (Germany, Austria, Netherlands) can be reached by using state-of-the-art flue gas cleaning techniques, but not without considerable effort.
In newly designed flue gas cleaning systems the following sequence of equipment is in principle often used:
- ESP;
- multi-staged wet scrubber with waste water evaporation;
- active cokes injection with fabric filter ('Flugstromadsorber');
- SCR-DeNOx.

This scheme with separate waste water evaporation is presented in figure 9. Figure 10 gives the sequence if the waste water evaporation is included in the flue gas cleaning route.

Instead of the ESP a fabric filter is also possible, but it is more expensive and it needs more careful operation and maintenance. If further proof is found of PCDD/F-formation in ESPs at temperatures below 200 °C [Vogg, Merz, 1990] this could mean that the fabric filter is preferred over the ESP.

The dry and semi-dry scrubbing techniques are capable of reaching removal efficiencies for dust, HF and non-volatile heavy metals equal to the wet scrubber. For HCl, SO_2 and volatile heavy metals, however, the performances are not so good as for the wet system. The strictest regulations can barely be met, and require a lot of adsorbent and consequently result in large amounts of residues [Reimann, 1992]. For this reason only smaller combustors might choose these techniques. Even existing (semi-)dry systems are now and then extended with a wet scrubber [Reimann, 1992].

The 'Flugstromadsorber' is often applied because of the low investment costs. Also the reduced risk of self-ignition because of the use of a mixture of active cokes with calciumhydroxide is a big advantage over the fixed bed technology. Of course the combination with calcium hydroxide increases the amount of residue enormously (mixtures contain 3-30 wt% of active cokes). The circulating fluid bed technology is a good alternative to decrease the amount of contaminated residue at slightly higher investment costs.
Besides PCDD/F removal an important function of the active cokes technique is to remove the last remaining acid gases, dusts and heavy metals for two reasons. First to have a buffer towards the emission limits in case of changing loads or sudden malfunctioning of other parts of the cleaning system. Second to ensure a dust- and acid-free flue gas and thus to prolong the lifetime of the following SCR-installation.
The fixed bed active cokes filter has relatively high investment costs and high consumption of active cokes (and subsequently a relatively large waste cokes stream). Therefore this technique will probably only be applied if very high removal efficiencies are required.

If the NO_x-limit is set at 200 mg/Nm^3 it might be cheaper to use SNCR instead of SCR because of the smaller investment and the easy operation. If the limit drops to 70 or 100 mg/Nm^3 SNCR needs high stoichiometric ratios of NH_3, which then requires extra NH_3-removing techniques.

2.6.5 Residue treatment

From the residues in general only the bottom-ash can be reused at the time. Before reuse the bottom-ash is crushed and iron scrap is removed. Several processes are under development to improve the bottom-ash quality to ensure disposal of the bottom-ash when the regulations are toughened. The bottom-ash which is not reused is landfilled, but because of the large amount of bottom-ash which is produced through MSW combustion great pressure (from the government) is executed to reuse as much bottom-ash as possible.

For fly-ash reuse is in fact not possible at the time: it is landfilled stacked in big bags ore fixated with cement or binder. Processes are under development to decrease the PCDD/F- and heavy metal content of the fly-ash prior to landfill, to reduce pollution risks due to leaching when landfilled. In future research will be executed to reuse fly-ash after treatment.

Flue gas cleaning residues are landfilled completely (in big bags). At the time no processes are ready to treat the residues in order to improve landfill or reuse characteristics. Only the waste water of wet scrubbers can be used to produce concentrated hydrogen chloride, common salt or gypsum. In most cases, however, the waste water is purified in a waste water cleaning process and released in the sewers or the water is evaporated and the remaining solids are landfilled.

Finally active cokes residues are combusted, until now in rotary kilns designed for chemical waste combustion. Other (combustion) options are under development.

As the emissions to the air are to a great extent controlled now by the state-of-the-art, research is more and more focusing on residues (diminishing of the total amount and improving the quality for recycling and landfill).

3 Retrofitting of existing installations

It will be clear that not all the existing installations consist of state-of-the-art technology: a lot of the combustion facilities which are in operation today have been built in the sixties and seventies. Improving their technical level can be realised by modernization though there are restrictions as to what can be changed. Too much changes might make it more profitable to demolish and reconstruct.

Most modernizations, which are executed are aimed at reducing the emissions of a certain facility, very often because emission legislation has gotten so tight that the facility cannot comply with the emission limits anymore.

In this chapter this kind of retrofitting (adjusting the flue gas cleaning system) is considered. For several classes of existing MSW combustion facilities one possible series of measures is discussed, to reduce the emissions to the level required by the EC Directive on Hazardous Waste Combustion (HWC).

These classes of **existing** MSW facilities are divided, based on the flue gas cleaning equipment installed, as follows:

a. no flue gas cleaning;
b. only a dust removal device: fabric filter, electrostatic precipitator or (multi)cyclone;
c. a dry scrubber;
d. a semi-dry scrubber;
e. a wet scrubber with only one stage (acid scrubbing);
f. a wet scrubber with two stages (acid and neutral scrubbing).

It is assumed that facilities which have a dry, semi-dry or wet scrubber installed also have a dust removal device.

Adjusting these classes of flue gas cleaning to a level which is able to meet the emissions set in the Directive is assumed to require a number of measures. These measures are presented in table 3.1. Basically for all categories the following flue gas cleaning system is seen as the ideal sequence (based on the state-of-the-art description in chapter 2): electrostatic precipitator, multi-stage wet scrubber, active cokes injection with a fabric filter (entrained flow adsorber (EFA) or 'Flugstromadsorber'). Ofcourse, there is no DeNOx-system required as the EC Directive has no NO_x emission limit (see figure 9, without the SCR DeNOx).

An exception is formed for the dry and semi-dry scrubber. According to some [Morun et al,1991;Matthes,1991;Kempin,1991;and others] these installations are capable of reaching emissions at a level of the EC directive on HWC when special additives (adsorbentia) are applied: combinations of calciumhydroxide (dry) or lime slurry (semi-dry) with active cokes. Others doubt whether it is possible to reach the required limits in this way. However, as dry and semi-dry scrubbers use much more additive and produce larger amounts of (solid) residues than wet scrubbers, replacing a dry or semi-dry scrubber by a multi-staged wet scrubber could be profitable (high additive and disposal costs). In this study for dry and semi-dry scrubbers two options are considered as can be seen in table 3.1.

Finally, for all installations which have or are retrofitted with a wet scrubbing system the option is considered whether the waste water from the scrubbers is to be evaporated or not. The chosen system implies waste water treatment as described in chapter 2: neutralization of the acid (with $Ca(OH)_2$), flocculation and precipitation (with $FeCl_3$, poly-electrolyte and TMT-15) of a (gypsum)sludge. The remaining water stream which contains high concentrations of chloride (as $CaCl_2$) can be disposed of in a river or sea or can be evaporated, producing a solid residue of salts. Usually the evaporated waste water is condensed and used again in the scrubber (1st stage).

Table 3.1 Measures per flue gas cleaning category to meet emission levels as set in the EC Directive on Hazardous Waste Combustion [EC Directives, 1992]

Categories flue gas cleaning (see text)		**ESP**	**Wet scrubber**	**Entrained flow adsorber**	**Additive injection**
a. without		X	X	X	
b. only dust			X	X	
c. dry	option 1 1)				X
	option 2 2)		X	X	
d. semi-dry	option 1 1)				X
	option 2 2)		X	X	
e. wet	1-stage 3)		X	X	
f. wet	multi-stage			X	

1) This option assumes that the use of extra/changed additives is sufficient to reach emissions at a level of the EC Directive on HWC

2) This option assumes that the dry or semi-dry scrubber is not capable of fulfilling the emission requirements of the EC Directive on HWC

3) A 1-stage wet scrubber is retrofitted with a second stage: it is assumed that the first stage does not need to be replaced but can be maintained

In practice it happens that some utilities which normally would be installed when retrofitted are already available: for example a water treatment installation nearby, or a heat exchanger which can be used. Of course, this will make the retrofitting easier and/or cheaper. The opposite is also true: often retrofitting is more expensive than calculated here because there are circumstances which prohibite the easiest/cheapest way of retrofitting and which require extra measures: for example if there is not enough space available or if there is no disposal possibility for a certain residue.

These circumstances, which are determined by local factors are not taken into account in this study. It is impossible to foresee all these factors and attach a cost figure to it in general.

4 MSW combustion facilities in Europe

In this chapter the totals and averages of all the countries, considered in this study, are presented and compared. Data per country can be found in Appendix A. The comparison between countries must be made very carefully due to the (possible) differences in definitions of (parts of) the Municipal Solid Waste in the different countries. In this study Europe stands for: the EC-member countries plus Austria, Switzerland, Norway, Sweden and Finland.

The survey presented refers to the situation in 1991 for the figures on amount, composition and treatment of MSW. As far as the MSW combustion facilities are concerned the data refer to July 1st, 1993, as much as possible. Only for France and Italy it was not possible to obtain the complete information which we would like to have for this study.

In general the information on the future developments is scarce and uncertain. This is mostly due to the fact that though there might be plans to built combustion facilities, these are often delayed, changed or cancelled because of public opposition. Another factor which makes planning vague is the uncertainty on what will be the possibilities for prevention and recycling in the near future: nobody wants to install an overcapacity for MSW combustion but on the other hand landfill has to be minimized as much as possible. The only way to realise minimal landfilling, if the possibilities for prevention and recycling cannot live up to the expectations, is through combustion.

4.1 Total amount of Municipal Solid Waste and the composition (putrescibles/paper/plastics/etc.) thereof generated in Europe per year

Before the amounts and composition of the MSW in Europe is presented it is necessary to define what is meant with MSW and what belongs to which fraction within MSW.

In this study the amount of waste produced in a certain country is the amount after prevention but before recycling. Separately collected waste thus is included. Here Municipal Solid Waste is generally understood to be the total of:
- household waste;
- bulky waste;
- comparable wastes from small commercial or industrial enterprises;
- market and garden residuals;

as far as it is collected and treated by or for the municipalities. For some countries, however, the definition of MSW is slightly different.

The composition of MSW is determined by sorting analyses. This is mainly done by sieving and picking by hand.
Among the different countries there are differences in the sorting fractions. In this study the following fractions are chosen:

- Putrescibles/Fines
- Paper and Cardboard
- Plastic
- Glass
- Metals
- Textiles
- Miscellaneous combustibles
- Miscellaneous non-combustibles

Most sorting analyses result in a fraction fines, but because of different sieve diameters these fractions are not comparable. As a great part of the fines, however, consists of putrescibles (kitchen/yard waste, etc.), it is counted to that group in this study.

The fraction 'miscellaneous combustibles' consists of wood, leather, rubber, etcetera. 'Miscellaneous non-combustibles' stands for minerals, stones, bones, etcetera.

When a product consists of two or more fractions it is counted to the dominating fraction. This means that a waste item which is 70% textile and 30% plastics is considered to be 100% textile.

Apart from differences in the definitions used there is also great fluctuation in the composition of MSW due to differences in social conditions, living structure, geographical location and the season in which the waste is produced. This explains why even figures of one country can show considerable differences in the amount and composition of the waste which is generated.

Compositions reported in literature often do not mention the definitions along with the figures. This makes comparison very difficult. Especially if not all the figures which are of interest to this survey are taken into consideration in a literature source. The gaps in the information then has to be filled in with figures from other reports, with possible other definitions. Another problem with figures from literature are the so-called primary and secondary sources. Primary sources actually analyse (fractions of) the waste whereas secondary sources copy or refer to the results of others. While copying definitions are lost or estimates are interpreted as truly measured. As primary sources are outnumbered by far by the secondary sources it requires an enormous effort to obtain good figures. This effort has been made for this study.

This report, which in fact also will be a secondary source, relies as far as possible on primary sources. However, these primary sources sometimes are relatively old and possibly outdated. If this appears to be the case or if no primary reference is available, an educated guess is made and reported.

In Europe a total population of 357 million people is living, producing a total of 140,880 ktonnes of Municipal Solid Waste per year (in 1991). Per capita this is an amount of 395 kg per year. The total amount of MSW produced in each country is given in table 4.1 as well as the production per capita. Also the composition of the MSW per country is listed. A mean composition for the whole of Europe is given as a reference.

From table 4.1 it can be seen that the countries with relatively high standards of living also produce relatively more waste. An exception to this is formed by Austria, Germany and Sweden where on a basis of economy a higher amount of waste would be expected. In Germany and Sweden prevention of waste is relatively well established, whereas the low amount in Austria is known to be influenced by a difference in definition.

There are large differences in the composition of the MSW between the different countries; e.g. between Germany, Austria and Switzerland, countries which are expected to have comparable standards of living. Nevertheless in Germany 44% of the waste is putrescibles/fines and 24% is paper, whereas for Austria and Switzerland these fractions are equally represented at 30% (table 4.1).
Ireland, Greece, Portugal and Spain are high in putrescibles/fines, but for Italy the putrescibles/fines content is on average (for Europe) whereas for France the lowest content is reported, together with Norway. However, this might be influenced by some differences in definitions: France and Norway have the lowest content of putrescibles but also the highest content of miscellaneous. This suggests a difference in the definition of the fraction putrescibles/fines between the countries.

Table 4.1 *Composition of Municipal Solid Waste per country in Europe*
All figures consider total MSW per country

Country	**Amount of MSW**		**Putrescibles/ fines Wt%**	**Paper Wt%**	**Plastic Wt%**	**Glass Wt%**	**Metals Wt%**	**Miscell (textiles incl.) Wt%**
	k tonnes /yr	**kg/capita**						
A	2,800	370	30	30	9	10	4	17
B	3,500	350	47	28	7	7	4	7
CH	3,700	550	30	31	13	7	6	13
D	25,000	410	44	24	7	9	6	10
DK	2,600	510	40	35	5	4	5	11
E	13,300	340	49	20	7	8	4	12
F	20,000	360	25	30	6	12	5	22
GR	3,150	310	53	18	7	3	4	15
I	17,500	300	40	22	7	8	3	20
IRL	1,100	310	55	20	10	3	3	9
L	180	480	47	28	7	7	4	7
N	2,000	470	25	32	7	4	4	28
NL	7,700	520	38	35	7	7	5	8
P	2,650	260	60	22	4	3	4	7
S	3,200	380	30	40	9	7	3	11
SF	2,500	500	30	40	6	4	3	17
UK	30,000	520	42	28	7	8	9	6
Europe	140,880	395	40	27	7	8	6	13
min-max[1]		260-550	25-60	18-40	4-13	3-12	3-9	6-28

[1] Minimum and maximum encountered, not based on standard deviation

4.2 Municipal Solid Waste treatment schemes (recycling, landfill, combustion)

All the MSW is disposed of in mainly 4 different ways: combustion, recycling, landfill and composting. The figures in this study do not include the treatment of residues from composting or combustion. For example: if a certain amount of residue from combustion is landfilled this amount is not included in the figure for landfill. This is done for two reasons:

- First of all it is not known precisely how much residue is generated and what is done with the residues from combustion or composting: in theory composted MSW is used as fertilizer whereas in practice it is often landfilled.
- The second reason is that residues from these processes are often considered chemical or special waste and therefore have to be landfilled on special sites, separately from regular MSW.

Table 4.2 gives an overview of how the waste is treated in Europe (in 1991). The values for Europe serve as a reference and represent the average for the countries considered.

The (scarce) information available on Greece did not give evidence on any combustion, recycling or composting so it was assumed that all the MSW is landfilled.

From table 4.2 it is apparent that the Mediterranean countries (E, GR, I, P) have a relatively high level of landfill. The same goes for Ireland, the United Kingdom and Finland.

Furthermore the relatively high level of recycling in Spain and the relatively low level of recycling in Belgium, Luxembourg, France and Austria are noticeable.

Table 4.2 Treatment of Municipal Solid Waste per country in Europe
All figures (except amount) in Wt% of the total MSW per country

Country	Amount ktonnes/yr	Combustion	Landfill	Composting	Recycling
A	2,800	11	65	18	6
B	3,500	54	43	0	3
CH	3,700	59	12	7	22
D	25,000	36	46	2	16
DK	2,600	48	29	4	19
E	13,300	6	65	17	13
F	20,000	42	45	10	3
GR	3,150	0	100	0	0
I	17,500	16	74	7	3
IRL	1,100	0	97	0	3
L	180	75	22	1	2
N	2,000	22	67	5	7
NL	7,700	35	45	5	16
P	2,650	0	85	15	0
S	3,200	47	34	3	16
SF	2,500	2	83	0	15
UK	30,000	8	90	0	2
Europe	140,880	24	63	6	8

Comparison of the figures presented here as the amount which is combusted in a certain country with the total combustion capacity installed in that country might lead to confusion as these figures will hardly ever match. These figures come from different sources and mismatches in the comparison can be caused by several factors:

- **definition**: the waste which is combusted might not have the same composition as the MSW which is produced; sometimes not only MSW is combusted but also industrial waste, sewage sludge, etc. A clear example of this confusion is Denmark. If the total combustion capacity in Denmark is related to the amount of MSW, the outcome is that around 70% of the Danish MSW is combusted. However, in the Danish combustors also industrial waste and some other kinds of waste are combusted, so that actually 'only' 48% of the Danish MSW is combusted.
- **operating hours**: the design capacity in tonnes per hours is multiplied by an assumed number of hours in operation of 7,000 per year. In The Netherlands, however, the average is much higher: 7,500-8,000 hours per year, whereas in other countries installations sometimes are not run 24 hours a day but only in daytime shifts. In Germany and Switzerland it is very common to build an extra unit to ensure waste disposal. This means that a plant with four units has a theoretically maximum availability of 75% (circa 6600 hours per year). Differences in operating hours are also caused by differences in maintenance practices: e.g. is the boiler cleaned once a year or once every two years?
- **increasing heat of combustion**: the heating value of the MSW has increased considerably over the last two decades [Dirks, 1991]. Because combustion facilities are limited in the amount of heat which can be generated per time period this means that at a certain point the increase of heat content per kg MSW had to

be compensated by a decrease of MSW throughput. This caused these installations to combust less MSW then according to design specifications [Dirks, 1991; Rijpkema et al, 1991].

4.3 Emission Guidelines in Europe

Almost each country in Europe (considered in this study) has its own legislation concerning emissions from MSW combustion. These regulations, however, differ a lot from country to country, not only in emission limits, but also in the number of pollutants for which there are limits. Some regulations only set limits to the emissions of dust, HCl, HF and CO, whereas others also imply SO_2, NO_x, total organic carbon (TOC), heavy metals, PCDD/F (polychlorinated dibenzo-para-dioxines and -furans) as well as certain performance demands, other than emissions.

Table 4.3 gives an overview of the emission limits conform the different regulations existing in Europe. For comparison the latest EC directive on Hazardous Waste Combustion (HWC) has also been included. The values in this table are related to an oxygen concentration in the flue gases of 11 vol% (dry, at standard temperature and pressure (stp): 273 K, 101.3 kPa) except for Norway (10 vol% O_2) and Sweden (10 vol% CO_2). An oxygen concentration of 11 vol% is assumed to correspond with a CO_2 concentration of 9 vol%.

Most of the regulations also require certain conditions to be met for the flue gases after the last (combustion) air injection. For example the German regulation requires that the flue gases, after the last injection of (combustion) air remain at a temperature of at least 850 °C and a concentration of 6 vol% O_2 (dry, at stp) for at least 2 seconds. This is meant as a sort of guarantee for destruction of combustible matter in the flue gases. What conditions are required is also mentioned in table 4.3.

Besides the limit values it is very important to specify the time period during which the measurements have to be averaged to meet the limit values. For example a limit value as a half hour average is more difficult to meet as the same value over a longer period of time (time to even out peaks). The remarks to the time basis for the limits are mentioned below per guideline.

Member countries of the European Committee have to comply with the EC-directive at minimum, but can have stricter limits. This is the case for Germany and The Netherlands.

Spain, France, Greece, Portugal, Ireland and Luxembourg do not have regulations of their own and only have the EC-directive to deal with. Belgium, Denmark, Italy and the United Kingdom have made small extensions to the EC-directive.

From the non-member countries Austria and Switzerland have stricter guidelines than the EC proposes. Norway and Sweden have comparable guidelines whereas Finland does not have a guideline but follows the EC-directive.

Some of the guidelines mentioned in table 4.3 have further regulations. These are mentioned briefly below.

Table 4.3 Emission guidelines for Municipal Solid Waste combustion in Europe (see text for explanation)

Component		**A** **1989**	**B** **1982**	**CH** **1991**	**D** **1990**	**DK** **1991**	**I**	**N**	**NL** **1989**	**S**	**UK** **1992**	**EC** **1989 MSW**	**EC** **Haz. waste**	**Component**
Dust	mg/Nm^3	15	100	10	10	30	30	10	5	20	30	30	5	Dust
HCl	mg/Nm^3	10	100	20	10	50	50	100	10	100	30	50	5	HCl
HF	mg/Nm^3	0.7	5	2	1	2	2	-	1	1	2	2	1	HF
SO_2	mg/Nm^3	50	-	50	50	300	300	300	40	200	300	300	25	SO_2
CO	mg/Nm^3	50	1000	50	50	100	100	100	50	100	100	100	50	CO
NO_x (as NO_2)	mg/Nm^3	100	-	80	200	-	-	-	70	400	350	-	-	NO_x (as NO_2)
TOC (as C)	mg/Nm^3	20	-	20	10	20	20	-	10	-	20	20	5	TOC (as C)
Heavy metals														Heavy metals
Hg	mg/Nm^3	0.05	-	0.1	0.05	-	-	0.1	0.05	0.03	0.1	0.2	0.05	Hg
Cd	mg/Nm^3	0.05	-	0.1	-	-	-	-	0.05	-	0.1	0.2	-	Cd
Hg+Cd	mg/Nm^3	-	-	0.1	-	0.2	0.2	-	-	-	-	-	-	Hg+Cd
Cd+Tl	mg/Nm^3	-	-	-	0.05	-	-	-	-	-	-	-	0.05	Cd+Tl
Pb	mg/Nm^3	-	-	1	-	1	-	-	-	-	-	-	-	Pb
Zn	mg/Nm^3	-	-	1	-	-	-	-	-	-	-	-	-	Zn
Pb+Zn+Cr	mg/Nm^3	2	-	-	-	-	-	-	-	-	-	-	-	Pb+Zn+Cr
Pb+Cr+Cu+Mn	mg/Nm^3	-	-	-	-	5	5	-	-	-	-	5	-	Pb+Cr+Cu+Mn
As+Ni	mg/Nm^3	-	-	-	-	1	-	-	-	-	-	1	-	As+Ni
As+Co+Ni	mg/Nm^3	0.5	-	-	-	-	-	-	-	-	-	-	-	As+Co+Ni
Tot.rest	mg/Nm^3	-	-	-	0.5	-	-	-	1	-	1	-	0.5	Tot.rest
PCDD/F	ng TEQ/Nm^3	0.1	-	-	0.1	-	4000 1)	2	0.1	0.1	1	-	0.1	PCDD/F
Conditions		11% O_2	11% O_2	11% O_2	11% O_2	11% O_2	11% O_2	10% O_2	11% O_2	10% CO_2	11% O_2	11% O_2	11% O_2	Conditions
Temperature	°C		800		850	850	950	800	850		850	850	850	Temperature
Residence time	s		1		2	2	2	1.5	2		2	2	2	Residence time
Oxygen conc.	vol%		6		6	6	6	-	6		6	6	6	Oxygen conc.

Sources:
Austria: Luftreinhalteverordnung (LRV 1989) [Löffler, 1991]
Belgium: capacity > 0.75 t/h [Jaubin, Wijs 1991]
Switzerland: Luftreinhalteverordnung [DK-Teknik, 1991, Löffler, 1991]
Germany: [17BImSchG, 1991]
Denmark: Emission limits for Waste combustion. Stat. Order 4th Jan. 1991 [Miljostyrelsen, 1991]
Italy: [Löffler, 1991]
Norway: [Pettersen, Nåmdal, 1992]]
Netherlands: [Besluit luchtemissies afvalverbranding, 1993]
Sweden: Solid waste management in Sweden, August 1990 [ISWA, 1991]
UK: Environmental Protection Act, Process Guidance Note IPR 5/3 [NMSO, 1992]
EC MSW [European Directives, 1989]
EC Hazardous waste combustion [European Directives, 1992]

[1] ng/Nm^3, *not* expressed as TEQ

- no limit value
(blank) not known

ALL VALUES FOR DRY GASES AT 273 K
AND 101.3 kPa

Austria [Löffler, 1991]
The Austrian guideline also requires a CO/CO_2-ratio of 0.002.

Belgium [Jaubin, Wijs, 1991]
The old Belgian regulation (given in table 3.1) also requires a greyness of the plume of less than 3 on Bacharach's scale and the following immission limits (half hour average):

- SO_2 0.1 mg/Nm^3
- HCl 0.1 mg/Nm^3
- HF 0.004 mg/Nm^3
- dust (< 10 μm) 0.1 mg/Nm^3

The Belgian government has adopted the EC-regulations, so in fact the guideline mentioned in table 3.1 will soon be replaced by the EC-Directive. An exemption is proposed to be made for combustors with a capacity of more than 30 tonnes per hour. These will then have to comply with the German emission limits except for NO_x, which will have to be 100 in stead of 200 mg/Nm^3.

Germany [17.BImSchG, 1991]

- The emission of the remaining heavy metals which according to table 4.3 has to be less than 0.5 mg/Nm^3 is supposed to be the total of the emissions of: As, Sb, Pb, Co, Cr, Cu, Mn, Ni, V and Sn.
- The emission values given in table 3.1 are daily averages. Besides this also half hour averaged limits are set:
- dust 30mg/Nm^3
- HCl 60mg/Nm^3
- HF 4mg/Nm^3
- SO_2 200mg/Nm^3
- NO_x 400mg/Nm^3
- TOC 20mg/Nm^3

For CO a one hour average of 100 mg/Nm^3 and a daily average of 50 mg/Nm^3 may not be exceeded. Also 90% of the CO-measurements in 24 hours have to be below 150 mg/Nm^3.
Finally the values for heavy metals and PCDD/F are averaged on the sampling time used.

- This 17.BImSchG is valid for new installations. For existing installations the emission limits will be valid starting 01-03-1994. Exceptions can be made until 01-12-1996.
- Starting up and closing down of the combustor has to be done with auxiliary burners (not burning waste). Waste is only allowed in the combustion chamber if the temperature in the chamber is above 850 °C.
- MSW combustors are obliged to recover energy. If more than 0.5 MW of energy is produced in excess of the internal need for energy electricity has to be generated.
- The following parameters have to be monitored continuously:
  - the emissions of CO, dust, HCl, HF (not if HCl-cleaning is applied), SO_2 and NO_x;
  - the percentage O_2 in the flue gases;
  - the temperature of the flue gases in the required areas;
  - parameters needed for sensible operation (e.g. pressure, humidity and volume of the flue gases);
- If chemical waste is burned the required temperature is set at 1200 in stead of 850 °C.

- If only liquid wastes are burned the O_2-concentration must be above 3 instead of 6 vol%.

Denmark [Miljostyrelsen, 1991a]

- The values for dust and HCl are weekly averages. Besides that also daily averages are set: dust 40 mg/Nm^3 and HCl 65 mg/Nm^3. These values may be exceeded by up to 30%. For CO a one hour average of 100 mg/Nm^3 may not be exceeded. Also 90% of the CO-measurements (30 min. average) in 24 hours has to be below 150 mg/Nm^3. The other values are averaged on the sampling time used.
- CO, dust, HCl and the temperature have to be monitored on a continuous basis. The other components must be checked via sampling 6 times a year. If they comply with the limits each time this frequency drops to two times a year.

France

France has adopted the EC-guideline with one exception:

- Hg + Cd < 0.2 mg/Nm^3

Norway [Pettersen, Nåmdal, 1992]

The existing regulations for small plants (capacity < 2 tonnes per hour) only sets a limit to the dust emission: 100-250 mg/Nm^3 at 10 vol% O_2 (dry, stp) in the flue gases. These regulations will probably be sharpened in the near future:

- dust 30-100 mg/Nm^3
- HCl 100-200 mg/Nm^3
- Hg 0.1 mg/Nm^3
- CO 100 mg/Nm^3

The Netherlands [Besluit Luchtemissies afvalverbranding, 1993]

- This guideline is valid starting 21-2-1993 for new installations (started after 1-4-1990). Existing installations will have to comply with this regulation by 01-01-1995.
- The emission of the remaining heavy metals which according to table 4.3 has to be less than 1 mg/Nm^3 is supposed to be the total of the emissions of: As, Sb, Pb, Co, Cr, Cu, Mn, Ni, V, Se, Te and Sn.
- The emission limits set in table 3.1 are hourly averages, except for PCDD/F and the heavy metals.
- For the emission limit for Hg an exception can be made if a removal efficiency of 90% (for Hg) can be demonstrated. For this reason the concentration of Hg in the raw (= uncleaned) flue gases has to be measured also.
- Starting up and closing down of the combustor has to be done with auxiliary burners (not burning waste). Waste is only allowed in the combustion chamber if the temperature in the chamber is above 850 °C.
- The following parameters have to be monitored continuously:
  - the emissions of CO, dust, HCl, TOC, SO_2 and NO_x;
  - the percentage O_2 in the flue gases;
  - the temperature of the flue gases in the required areas.

  The emission of dust, heavy metals, HCl and HF have to be measured 4 times a year and of PCDD/F 2 times a year. For this each time three samples per chimney have to be taken.
- A combustion facility has to consist of two units at least to guarantee the continuity of the operation.
- Existing installations can get a PCDD/F exemption up to 0.5 ng TEQ/Nm^3 if it is proven that reaching 0.1 ng would require excessive investment.

- For existing installations the NO_x-limit of 70 mg/Nm^3 is a guidance value which they have to try to meet.

Sweden [Svenska Renhållningsverks-Föreningen,1991;Kuusisto,1992]
- The limits for dust and HCl are monthly averages, whereas the CO-limit is hourly averaged.
- For existing plants the limit for Hg is 0.08 mg/Nm^3 and for PCDD/F 2 ng/Nm^3.

United Kingdom [HMSO, 1992]
- This guideline came into effect in August 1992. New plants and substantially changed plants will have to comply with these regulations directly. Existing plants have until 1 December 1996 to comply with the limits. Starting 1 August 1992 existing plants only have one emission limit to comply with: 100 mg/Nm^3 total particulate matter.
- The emission of the remaining heavy metals which according to table 4.3 has to be less than 1 mg/Nm^3 is supposed to be the total of the emissions of: As, Pb, Cr, Cu, Mn, Ni and Sn.
- For PCDD/F the emission limit is 1 ng TEQ/Nm^3; the operators, however, are urged to reduce this emission as far as possible with an aim of 0.1 ng TEQ/Nm^3.
- The process should not give rise to an offensive smell noticeable outside the premises where the process is carried on.
- During normal operation, including start-up (with 5 minutes delay) and shut-down emissions should be free from visible smoke.
- Starting up and closing down of the combustor has to be done with auxiliary burners (not burning waste). Waste is only allowed in the combustion chamber if the temperature in the chamber is above 850 °C.
- The limits set in table 4.3 are valid for non-continuous monitoring. If they are continuously monitored 95% of the hourly averages should not exceed the emission value in table 4.3. The peak hourly average should not exceed 1.5 times the emission value.
- For CO a one hour average of 100 mg/Nm^3 may not be exceeded. Also 95% of the CO-measurements (10 minutes averages) taken in 24 hours have to be below 150 mg/Nm^3.
- For existing installations with a capacity > 6 tonnes per hour the conditions (850 °C, 2 seconds, 6 Vol% O_2) will have to be implemented by 1 December 1996, or at the latest when the furnaces are replaced. The other installations (capacity < 6 tonnes per hour) have until 1 December 1995 to comply with the following conditions: 850 °C and 6 Vol% O_2 for a sufficiently long time.

EC-directive MSW combustion [European Directives, 1989]
- The values in table 4.3 are directly valid for new installations with a capacity of more than 3 tonnes per hour. Installations with a capacity of more than 1 but less than 3 tonnes per hour have the following limits: dust 100 mg/Nm^3, HCl 100 mg/Nm^3, HF 4 mg/Nm^3, CO 100 mg/Nm^3 and TOC 20 mg/Nm^3. In addition the limits for heavy metals in table 4.3 apply. Installations smaller than 1 tonne per hour have the following limits: dust 200 mg/Nm^3, HCl 250 mg/Nm^3, CO 100 mg/Nm^3 and TOC 20 mg/Nm^3.
- Existing installations larger than 6 tonnes per hour have to comply with the values in table 4.3 starting 01-12-1996. Existing installations with a capacity of smaller than 6 tonnes per hour have to comply with the limits for new installations (see above) starting 01-12-2000. By 01-12-1995 the existing installations have to comply with the following limits:

  - capacity < 1 tonne/hour: CO 100 mg/Nm^3 and dust 500 mg/Nm^3;
  - capacity > 1 but < 6 tonnes/hour: CO 100 mg/Nm^3 and dust 100 mg/Nm^3.
- For existing installations the conditions 850 °C and 6 vol% O_2 for at least 2 seconds need only to be fulfilled from the moment the combustor is modernised.
- 90% of the CO-measurements in 24 hours have to be below 150 mg/Nm^3. For existing installations the CO-limit of 100 mg/Nm^3 is hourly averaged for installations larger than 1 tonne per hour and daily averaged for the smaller ones.
- New installations larger than 1 tonne per hour have to monitor the emissions of dust, CO and HCl and also the O_2-concentration and the temperature continuously. Heavy metals, HF, SO_2 and TOC are to be measured by sampling. Small installations (< 1 tonne per hour) have to monitor the emissions of dust, HCl and CO and the O_2-concentration by sampling. The frequency of the sampling is to be determined by the permitting authorities.
- Existing installations have to monitor dust, CO and O_2-concentrations continuously (> 1 tonne/hour) or by sampling (< 1 tonne/hour) starting 01-12-1995, until the requirements for new installations have to be met (see above).

EC-directive Hazardous waste combustion (HWC) [European Directives, 1992]
- In June 1993 some amendments to this Directive were adopted. This could, however, not be integrated in this report anymore.
- This directive directly applies to new installations (starting 30-6-94). Existing installations (for which the first permit for operation was granted before 30-6-94) have until 30-6-97 to comply with this directive. Installations which will be definitely shut down before 30-6-99 and will not be operated for than 20,000 hours after 30-6-94 are exempted from the directive.
- The emission of the remaining heavy metals which according to table 4.3 has to be less than 0.5 mg/Nm^3 is supposed to be the total of the emissions of: As, Sb, Pb, Co, Cr, Cu, Mn, Ni, V and Sn.
- The emission values given in table 4.3 are daily averages. Besides this also half hour averaged limits are set:
  - dust 10 mg/Nm^3
  - HCl 10 mg/Nm^3
  - HF 2 mg/Nm^3
  - SO_2 50 mg/Nm^3
  - TOC 10 mg/Nm^3

  For CO a daily average of 50 mg/Nm^3 may not be exceeded. Also 95% of the CO-measurements (10 minutes average) in 24 hours have to be below 150 mg/Nm^3. Finally the values for heavy metals and PCDD/F are averaged on the sampling time used.
- The following parameters have to be monitored continuously:
  - the emissions of CO, dust, TOC, HCl, HF (not if HCl-cleaning is applied) and SO_2;
  - the temperature in the furnace;
  - the oxygen concentration, the pressure, the temperature and the water vapour of the flue gas;
- The heavy metal and PCDD/F emissions have to be measured periodically.
- If halogenated waste is burned the temperature must be raised to at least 1200 °C.
- If only liquid wastes are burned the O_2-concentration must be above 3 instead of 6 vol%.

- Starting up and closing down of the combustor has to be done with auxiliary burners (not burning waste). Waste is only allowed in the combustion chamber if the temperature in the chamber is above 850 °C (or above 1200 °C in case of halogenated waste). The auxiliary burners must automatically come into operation if the temperature is below 850 (or in case of halogenated waste 1200 °C.

  The waste feed is to be automatically stopped if the continuous measurements show that any emission limit value is exceeded due to malfunctioning of the flue gas cleaning system.

4.4 Overview existing Municipal Solid Waste combustors in Europe

In Europe there are 485 MSW combustors with a total nominal capacity of 6,160 tonnes per hour in operation at the time. All together these combustors have a capacity (based on 7,000 hours of operation per year) of 43,140 ktonnes per year. If this is compared to the total amount of waste which is actually combusted in Europe (table 4.2: 140,880 ktonnes MSW, 24% combusted = 33,810 ktonnes combusted) there is a considerable difference (for explanation see chapter 4.2). For the EC member countries there are 413 combustion facilities with a total capacity of 37,530 ktonnes per year.

Table 4.4 shows in which country the combustors are located and how much of the total MSW they combust.

First of all it should be mentioned that the information on the Italian combustors is vague. The situation in Italy is very confusing and it is not clear which installations are in operation and which are not. For this overview 28 combustors are assumed to be in operation. For 15 of these facilities it is not known what flue gas cleaning equipment they have installed. Also the information on France is not complete: though nearly all installations (except some very small ones: < 20 tonnes per day) are known, it is not known for a great part of these facilities (143 out of 225) what flue gas cleaning they have installed.

In table 4.4 it can be seen that France owns the most combustion facilities by far (225). However, these 225 combustors are relatively small as they represent 46.4% of the number of combustors in Europe but only combust 26.1% of the total European MSW. On the contrary the installations in Germany and The Netherlands are relatively large: 10.1% (Germany) and 2.1% (The Netherlands) of the combustors combust respectively 27.9% and 7.3% of the European MSW. The average for The Netherlands is, however, largely influenced by the presence of the worlds largest MSW combustor: AVR Rotterdam, capacity 950 ktonnes/year.

Greece, Ireland and Portugal do not have MSW combustors.

Table 4.4 MSW combustors in Europe

Country	Number of combustors per country	% of total number of combustors in Europe [%]	Combustion capacity per country [ktonnes/yr]	% of total combustion capacity in Europe [%]
A	2	0.4	340	0.8
B	24	4.9	2,240	5.2
CH	30	6.2	2,840	6.6
D	49	10.1	12,020	27.9
DK	30	6.2	2,310	5.4
E	15	3.1	740	1.7
F	225	46.4	11,330	26.1
I	28	5.8	1,900	4.4
L	1	0.2	170	0.4
N	18	3.7	500	1.2
NL	10	2.1	3,150	7.3
S	21	4.3	1,860	4.3
SF	1	0.2	70	0.2
UK	31	6.4	3,670	8.5
Europe	485	100.0	43,140	100.0
EC	413	85.2	37,530	87.0

In Europe most of the combustors recover energy from the flue gases (56% by number representing 82% of the MSW combustion capacity). Also this is very different per country. Surprisingly low is the energy recovery level in the United Kingdom. From comparing the percentages based on number of installations and amount of MSW processed it can be concluded that always the combustors which do recover energy are larger (in average) than the ones which do not.

Table 4.5 gives an overview of the level of energy recovery per country. The purpose of the recovered energy is mentioned in detail (as far known) in Appendix A per installation. In general, however, the Scandinavian countries use a high percentage of the recovered energy to produce hot water for district heating whereas the other countries mainly produce steam for electricity generation, with or without usage of the remaining energy.

Of course Greece, Portugal and Ireland are excluded from these table as they do not have any MSW combustion facilities.

Table 4.5 Level of energy recovery in the different countries in Europe

Country	Number of combustors per country	% of total number with energy recovery [%]	Combustion capacity per country [ktonnes/yr]	% of total capacity with energy recovery [%]
A	2	100	340	100
B	24	46	2,240	64
CH	30	80	2,840	90
D	49	100	12,020	100
DK	30	100	2,310	100
E	15	27	740	73
F	225	42	11,330	70
I	28	64	1,900	76
L	1	100	170	100
N	18	28[1]	500	83
NL	10	90	3,150	97
S	21	100	1,860	100
SF	1	100	70	100
UK	31	16	3,670	32
Europe	485	56	43,140	82
EC	413	54	37,530	80

[1] On 13 small incinerators it is assumed that no heat is recovered

Also the way the flue gases are cleaned differs a lot. In table 4.6 the flue gas cleaning used in Europe is showed. For this the installations which have scrubbers as well as dust removing equipment are only counted to the fraction with scrubbers. For a number of combustors in Italy (15) and France (153) and for 1 installation in Spain, the flue gas cleaning used is not known; they represent the fractions unknown in table 4.6. There are 10 combustors without flue gas cleaning: 7 in Spain and 3 in the United Kingdom.

Table 4.6 Extent of flue gas cleaning in MSW combustion facilities in Europe

Extent of flue gas cleaning	**MSW combusted**		**Installations**	
	ktonnes/year	**%**	**number**	**%**
Flue gas cleaning: [1]				
- unknown	4,800	11.1	169	34.8
- none	110	0.3	10	2.1
- only dust removed	11,640	27.0	136	28.0
- dry scrubber	2,750	6.4	34	7.0
- semi-dry scrubber	6,060	14.0	35	7.2
- wet scrubber, 1-stage	6,260	14.5	45	9.3
- wet-scrubber, 2-stage	8,000	18.5	45	9.3
- active cokes adsorption	3,520	8.2	11	2.3
Total	43,140	100.0	485	100.0

1) Installations which only have a dust removal device and no scrubber are calculated under only dust removal installations which have both are calculated under the scrubber. Installations which have active cokes adsorption equipment usually also have a scrubber and a dust removal device; they are only calculated under 'active cokes adsorption'

From comparing the percentages based on number of installations and amount of MSW processed it can be concluded that on average the combustors:

- with no flue gas cleaning are relatively small;
- of which the flue gas cleaning system used is unknown are relatively small;
- which use scrubbers are relatively large (on average), except dry scrubbers;
- which have an active cokes adsorption device are relatively large.

4.5 Future perspectives for Municipal Solid Waste combustors: new combustors, retrofits, closing

As to combustion facilities there is a lot of uncertainty. Most countries have plans for extension of the combustion capacity but in a number of countries (among others Germany and The Netherlands) the opposition from the public and from environmental groups is getting so strong that plans are postponed or even cancelled. Even if there is in principle no opposition to new combustion plants there still are enormous difficulties in finding suitable locations ('NIMBY' = Not In My Back Yard). Also in politics new combustion facilities are not always popular subjects ('NIMEY' = Not In My Election Year). The role that the alternatives for combustion (prevention and recycling) will play in future is uncertain which will make the planning of the combustion capacity very difficult. Too much combustion capacity is expensive and frustrates recycling and prevention efforts, whereas too few capacity will necessitate more landfill space (which is hardly or not available).

However, the lack of other solutions (presently available) will make the construction of new MSW combustors in the near future inevitable. Especially because due to stricter regulations old combustors will have to be shut down. Others will be retrofitted with flue gas cleaning techniques or improved process control systems.

All countries (which have combustors) expect the combustion capacity to grow in the next two decades, despite the efforts made to increase prevention end recycling.

In Appendix A the information on the future development of the combustion facilities per country is mentioned as far known.

5 Calculating a total emission

In order to calculate roughly what will happen to the total emission of pollutants if all the existing installations would be retrofitted such that they would comply with the EC Directive on Hazardous Waste Combustion (HWC) some estimates of the present emissions were made. Per category of existing flue gas cleaning (see table 4.6) an emission was assumed based on literature references as to what is generally achieved in practice at the moment in the different flue gas cleaning equipment parts.

In table 5.1 the emissions are presented which are assumed to be realised in installations which have the equipment installed according to the category they are in. The total emission then can be calculated by multiplying the number of tonnes which are combusted by 5140 Nm^3 flue gas per tonne of waste and by the concentration of the pollutant in the flue gas in mg/Nm^3 or ng I-TEQ/Nm^3.

The raw (= uncleaned) flue gas composition is calculated with a mass balance assuming a tonne of waste is combusted with an air factor of 1.8. The flue gas compositions are derived from this raw flue gas composition by using removal efficiencies for the separate flue gas cleaning equipment parts. The composition of the waste used, the calculation of the raw flue gas cleaning concentrations and the removal efficiencies are given in Appendix C.

As CO and unburnt hydrocarbons are not removed by flue gas cleaning these pollutants have been left out of this calculation. Also NO_x was left out because the EC Directive on HWC has no limit for NO_x.

Combustion facilities which have active cokes adsorption equipment installed, are assumed to comply with the EC Directives on HWC, which is also given in table 5.1 for comparison.

Table 5.1 Concentration[1] of pollutants in flue gas after different cleaning equipment (see texte)

Component	**None**	**Only dust removal**	**Dry scrubber**	**Semi-dry scrubber**	**Wet scrubber 1-stage**	**Wet scrubber stage-2**	**EC--Directive HWC**
Dust	4700	94.4	18.9	18.9	18.9	9.4	5
HCl	1060	1060	106	21.2	10.6	5.3	5
HF	0.2	0.2	0.04	0.02	0.01	0.002	1
SO_x (as SO_2)	270	270	135	54	162	14	25
Heavy metals							
- HG	0.4	0.36	0.25	0.22	0.07	0.04	0.05
- CD + TI	0.5	0.25	0.13	0.10	0.05	0.02	0.05
- rest[2]	31	6.2	1.86	1.24	0.62	0.31	0.5
PCDD/F	15	15	8	8	8	8	0.1

[1] All concentrations in mg/Nm^3, except PCDD/F, ng TEQ/Nm^3, at 11 vol-11% O_2, dry gases

[2] 'rest' stands for: Sb, As, Pb, Cr, Co, Cu, Mn, Ni, Sn, V

Of course, the given concentrations in table 5.1, are estimates which are considered to be generally true. Individual installations might perform better or worse.

In table 5.1 cyclones, electrostatic precipitators (ESP) and fabric filters (bag filters) are assumed to have similar performances. In reality this is not true, the dust removal efficiency varies: 80-95% for cyclones, 95-99.9 for ESP's and 98-99.99 for bag filters. However, in this study the performance was averaged, as distinction would cost too much effort to be realised within time frame and budget. Besides that, it proved that the result was not influenced dramatically by this assumption.
For the same reasons no difference was made between dry or semi-dry scrubbers with subsequent ESP or with subsequent bag filter.

As far as dioxins and furans (PCDD/F) are concerned an average emission was assumed. Especially this emission varies enormously between installations. Modern installations can realise PCDD/F emissions of 0.5 to 2 ng I-TEQ/Nm^3 without flue gas cleaning equipment, but for less modern installations emissions of 50 to 100 ng I-TEQ/Nm^3 are known to occur more than once [Johnke, Stelzner, 1991; Schetter, Horch, 1991; Slob et al, 1993]. This lead to the 'guess' that 15 ng I-TEQ/Nm^3 can serve as an average for the total of the existing installations.
Besides the uncertainty on the amount of PCDD/F in the raw flue gas it is also not known precisely what happens to the PCDD/F in the flue gas cleaning. For the esp, there have been measurements which gave evidence of an increase as well as a decrease of PCDD/F in the ESP: therefore it is here assumed to remain unchanged as an average. Scrubbers are assumed to remove approximatly 50% of the PCDD/F, partly because dust is removed in the scrubbers and a large part of the PCDD/F is attached to the dust particles [Güthner, 1990]. On the other hand, it has been reported that the total concentration of PCDD/F in ng I-TEQ/Nm^3 increases in a wet scrubber.
It is assumed that active cokes adsorption reduces the PCDD/F emission to the required level.

With these emission factors and the data on the facilities per country the total emission of certain pollutants per year is calculated. These figures are given in table 5.2.

It should be noted that the emission factors given in table 5.1 do not represent what is technically possible with the specified flue gas cleaning equipment, but what at the moment in general is achieved in practice. The emission factors are averages of what is in operation at this moment.

With these emission factors and the data on the facilities per country the total emission of certain pollutants per year is calculated. These figures are given in table 5.2.
In the table the total emission is presented at the moment and in case all MSW combustion facilities would reach the limits of the EC Directive on HWC. These emissions are not calculated by just using the emission limits of the EC Directive: only for dust, HCl and PCDD/F the limits according to the EC Directives are used. For the other compounds the emission factor is supposed to be equal to what can be realised by a 2-staged wet scrubber. This is done because for HF, SO_x and heavy metals the 2-staged wet scrubber realises emissions below the EC Directive. If for those compounds the Directive value would be used this would implicate that by

adapting the installaton in order to reach the limit for dust, HCl and PCDD/F the emission of HF, SO_x and heavy metals would increase. This is unlogical.

For installations of which the flue gas cleaning is unknown it is assumed that they have no flue gas cleaning at all.

Table 5.2 The total emission of pollutants per country per year

Total emissions per country

	dust ton/yr	HCl ton/yr	HF ton/yr	SOx ton/yr	Hg ton/yr	Cd+Tl ton/yr	Rest ton/yr	PCDD/F g/yr
A	9	9	0.003	24	0.07	0.03	1	0
B	815	8514	1.65	2518	3.41	2.27	53	148
CH	345	2504	0.50	889	1.51	0.91	19	133
D	838	1041	0.65	3767	6.45	3.28	43	417
DK	291	1590	0.42	1105	2.08	1.11	18	103
E	1859	4036	0.76	1028	1.38	1.03	32	57
F	98042	42143	8.19	12794	17.80	16.40	767	741
I	20237	8147	1.56	2389	3.15	3.10	154	131
L	16	18	0.02	47	0.19	0.09	1	7
N	84	509	0.11	468	0.31	0.22	4	24
NL	292	2124	0.43	829	1.36	0.82	17	91
S	279	1957	0.50	1550	1.97	1.15	20	86
SF	34	382	0.07	97	0.13	0.09	2	5
UK	3445	19969	3.77	5087	6.80	4.80	126	283
Total EC	125835	87583	17	29563	43	33	1210	1978
Total	126584	92944	19	32592	47	35	1256	2226

Percentage of the total European emission

	dust	HCl	HF	SOx	Hg	Cd+Tl	Rest	PCDD/F	Fraction of the total MSW combustion capacity in Europe
A	0.01%	0.01%	0.02%	0.07%	0.15%	0.10%	0.04%	0.01%	0.80%
B	0.64%	9.16%	8.86%	7.73%	7.32%	6.43%	4.21%	6.64%	5.20%
CH	0.27%	2.69%	2.70%	2.73%	3.24%	2.58%	1.52%	5.96%	6.60%
D	0.66%	1.12%	3.50%	11.56%	13.84%	9.28%	3.46%	18.73%	27.90%
DK	0.23%	1.71%	2.26%	3.39%	4.47%	3.15%	1.45%	4.65%	5.40%
E	1.47%	4.34%	4.09%	3.15%	2.97%	2.93%	2.52%	2.57%	1.70%
F	77.45%	45.34%	43.94%	39.26%	38.18%	46.44%	61.05%	33.29%	26.10%
I	15.99%	8.77%	8.37%	7.33%	6.76%	8.79%	12.23%	5.90%	4.40%
L	0.01%	0.02%	0.09%	0.14%	0.41%	0.24%	0.09%	0.31%	0.40%
N	0.07%	0.55%	0.61%	1.44%	0.67%	0.63%	0.33%	1.07%	1.20%
NL	0.23%	2.29%	2.29%	2.55%	2.91%	2.32%	1.35%	4.08%	7.30%
S	0.22%	2.11%	2.67%	4.76%	4.23%	3.26%	1.56%	3.84%	4.30%
SF	0.03%	0.41%	0.39%	0.30%	0.28%	0.26%	0.18%	0.24%	0.20%
UK	2.72%	21.49%	20.22%	15.61%	14.58%	13.60%	10.01%	12.70%	8.50%

Emissions if all the MWC facilities would comply with EC Directive on HWC

	dust ton/yr	HCl ton/yr	HF ton/yr	SOx ton/yr	Hg ton/yr	Cd+Tl ton/yr	Rest ton/yr	PCDD/F g/yr
Total EC	965	965	0.39	2701	8	4	60	19
Total	1109	1109	0.44	3104	9	4	69	22

Fraction of the present situation

	dust	HCl	HF	SOx	Hg	Cd+Tl	Rest	PCDD/F
Total EC	0.77%	1.10%	2.21%	9.14%	18.10%	11.73%	4.94%	0.98%
Total	0.88%	1.19%	2.38%	9.53%	19.02%	12.56%	5.47%	1.00%

In table 5.2 we can see that some countries have very low emissions whether others have very high emissions. Interpretation of these data on itself is not possible: the number and capacity of the installations involved is also important. For example: Austria, Luxembourg and Finland have relatively low emissions but also only 1 (Luxembourg, Finland) or 2 (Austria) combustion facilities. Another example: the amount of MSW which is combusted in Germany is around 6 times the amount which is combusted in Belgium, but the emissions are approximatly the same, except for PCDD/F (higher in D) and HCl (higher in B).
From combining the information presented in table 5.2 with table 4.4 a number of conclusions concerning the average level of flue gas cleaning can be drawn:
e.g. the German combustion facilities have a relatively high level of flue gas cleaning compared to the Italian combustors, since the German plants combust around 7 times the amount which is burned in Italy but the emissions are lower in Germany than in Italy.
In order to make these conclusions clearer in table 5.2 the % per country of the total emission of the pollutants in Europe is given. Comparing this percentage with the percentage of the European MSW combustion capacity in that specific country indicates whether the average flue gas cleaning level is relatively high or not.
From the table it becomes obvious that on average the level of flue gas cleaning is relatively high in Austria, Switzerland, Germany and the Netherlands (and to a lower extent in Denmark and Luxemburg) and relatively low in France, Italy and the United Kingdom.

Apppendix B gives a complete overview of the number and capacity of MSW combustion facilities per flue gas cleaning category and per country.

6 Costs of MSW combustion

In this chapter it will be described what costs are involved in building or retrofitting MSW combustion facilities. Chapter 6.1 deals with new facilities whereas in chapter 6.2 the retrofitting of existing faclities is discussed. In chapter 6.3 a total investment cost for retrofitting to an emission level as in the EC Directive on HWC will be calculated. Besides investments costs also the extra costs per tonne will be mentioned.

6.1 Designing new MSWC facilities

Starting from the information on the state-of-the-art description (see chapter 2), the costs (investment cost and cost per tonne) are calculated for combustion facilities which basically have the following equipment:

- a moving grate;
- a boiler in which steam is produced;
- a turbine and electricity generator;
- a flue gas cleaning system which consists of: an ESP, a 2-staged wet scrubber and an entrained flow adsorber (reactor with subsequent fabric filter) with active cokes addition.
- a waste water treatment system which neutralizes the waste water and precipitates a gypsum sludge and heavy metals.

The costs are given with and without evaporation of the waste water. The latter is done because it is not certain whether discharge of waste water will be allowed. (The waste water still contains a high concentration of salts (mainly chlorides) after purification in the waste water treatment system.) At the moment in most locations, which are near to the sea or to a river, discharge of waste water is still allowed, but how this will develop in future is not known. Therefore both options are considered here.

Waste water evaporation results in a solid salts residu which has to be landfilled (see also chapter 2). The evaporated waste water is condensed and used again in the first step of the wet scrubber.

In fact the new combustion facility is equivalent to the block scheme in figure 10, without the SCR DeNOx equipment, and with the waste water evaporation as an option. In this study we did not choose to evaporate the waste water in a spray dry absorber (as in figure 9), because of lack of data on the process operation and costs of such a flue gas cleaning system. The system becomes more complex and less flexible as the amount of water which can be evaporated in a spray dryer is limited, which puts high demands on the process operation of the scrubber.

The investment and operating costs were determined for different capacities in a range from 9 tonnes per hour to 115 tonnes per hour. With an availablty for the facility of 80% (7008 hours in operation per year) this equals annual capacities of 63,000 to 806,000 tonnes per year. These capacities and the number of units per plant were based on the following:

- Each plant must have 2 separate units at minimum: some guidelines (e.g. German, Dutch e.g.) require this as a measure to ensure waste disposal capability.
- Based on information on grate sizes the unit capacity ranges within 3 to 25 tonnes per hour: smaller plants are known to have difficulties to reach complete combustion (CO and C_xH_y emission limits) and at the time larger grates are seldom built because of mechanical problems.
- It is cheaper to have 2 large units than 5 small units.
- In order to compare the costs properly as much as possible the same number of units is used, unless the unit sizes go out of the specified range.

The number of units and their capacitiy for the different plant sizes considered here are given in table 6.1.

Table 6.1 Plant sizes and number of units

Number of units	Capacity per unit [tonnes per hour]	Plant capacity [tonnes per hour]	Plant capacity [ktonnes per year]
3	3	9	63
3	5	15	105
3	9	27	189
3	14	42	294
3	19	57	399
3	24	72	505
4	22	88	617
4	25	100	701
5	23	115	806

6.1.1 Investment costs

For the calculation of the investment costs a number of bid documents for projects which have been realised in the Netherlands were used. These bid documents were drawn up by international suppliers in the period of 1989 to 1992. This information has been complemented with data from feasibility studies and suppliers and with general engineering prices.

The investment costs were calculated using the following assumptions:
- The facility is a grass roots facility i.e. no special costs are included for local circumstances.
- Costs are based on the Dutch situation (price level 4th quarter 1992), excluding V.A.T.: 1 ECU is considered to equal 2.20 Dfl.
- All plant components are placed in industrial buildings.
- Plant utilities (natural gas, electricity, water, steam, etc.) are fully integrated in the overall plant design.
- All the investment costs for installation parts are inclusive of the attached equipment, for example the investment cost for the handling and storage of chemicals used in the scrubber are included in the investment cost for the scrubber.

In table 6.2 the investment costs for the plant capacities, as in table 6.1, are presented with and without waste water evaporation. The total investment appears to change considerably depending on whether the waste water is evaporated or not. These data are also presented in figure 11.

Table 6.2 Investment costs for a new MSW combustion facility, with or without evaporation of the waste water (explanation in text)

Plant capacity [ktonnes per year]	**Total investment *without* waste water evaporation [MECU]**	**Total investment *with* waste water evaporation [MECU]**
63	90.9	111.0
105	124.2	154.8
189	179.1	228.7
294	236.8	307.9
399	287.8	378.7
505	334.2	443.9
617	404.4	526.2
701	438.6	580.9
806	503.8	662.4

In order to make clear how these investment costs are built up the investment costs for an annual capacity of 505,000 tonnes per year are specified below. All figures consider the total for 3 units of 24 tonnes/hour in millions ECU (MECU).

Investment costs

Item	Waste water evaporation *without*	*with*
- Infrastructure[1]	3.6	3.6
- Buildings	32.5	32.5
Subtotal investment building/construction (BCI)	36.1	36.1
- Shredders	3.0	3.0
- Grates	20.6	20.6
- Boilers	33.0	33.0
- Turbines/generators [2]	19.7	17.1
- ESP	5.6	5.6
- Scrubbers	5.0	5.0
- Active coal reactor + bag filter	4.7	4.7

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[1] No cost for the ground property is calculated

[2] Because for the evaporation of the waste water steam is used, the turbine, if waste water evaporation is applied, is smaller than without waste water evaporation

- Heat exchangers	1.5	1.5
- Fans	1.1	1.1
- Stacks	1.8	1.8
- Waste water treatment	14.1	14.1
- Waste water evaporation	0.0	42.4
- Slag treatment	5.1	5.1
- Emission measurement equipment	1.8	1.8
Subtotal investment electro/mechanical (EMI)	116.8	156.6
- Steel structure/ducting	8.0	18.6
- Electrical equipment	11.7	15.7
- Control and instrumentation	11.7	15.7
- Engineering	12.5	17.4
- Unforeseen/risks	16.1	22.4
- Spare parts	3.0	4.1
Subtotal investment general (GI)	62.8	93.7
Total direct investment (BCI+EMI+GI)	215.6	286.4
Indirect investment 1)	118.6	157.5
TOTAL Investment [MECU]	334.2	443.9
	=====	=====

6.1.2 Operation costs

Besides investment costs also the costs per tonne of MSW processed are important. These are calculated with the following assumptions:

- the availablity of the plant is 80%: this means that the plants are in operation for 7,008 hours per year.
- the depreciation period for a new MSW combustion facility is 25 years and the interest is 10%, which together renders an annuity of 11.02% per year;
- maintenance of the building/construction part is 1% of the investment for this part (BCI), maintenance for the electro/mechanical part is 5% of the investment for this part (EMI);
- personel costs 40,000 ECU per year per person;
- insurance is 1% of the total direct investment;

The prices of chemicals and utilities are as follows:

- calciumhydroxide	100	ECU/tonne
- iron(III)chloride	510	ECU/tonne
- TMT-15 (mercaptan)	18,200	ECU/tonne
- poly-electrolite	11,400	ECU/tonne

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1) Indirect investment mainly consists of: the interest during building, feasibility studies and investigations and procedures to obtain the permit (environemtal imact studies)

- active coal mixture (with $Ca(OH)_2$)	150	ECU/tonne
- water	0.91	ECU/tonne
- electricity	0.032	ECU/kWh

It is assumed that the bottom-ash can be reused and that the cost for disposal of the bottom-ash equals zero.
Disposal of the other residues (fly-ash, sludge, salts, used active coal mixture) is assumed to cost 182 ECU/tonne (400 Dfl/tonne).

All this leads to the costs per tonne as specified in table 6.3. These data are also shown in figure 12.

From these data we can see that from small to larger plants the costs per tonne decrease. Based on figure 12 it can be stated that under the assumptions made here, MSW combustion facilities should have at least a capacity of 300,000 tonnes per year, economically spoken. Evaporation of the waste water appears to increase the cost per tonne considerably. Also the influence of the number of units can be seen from the shape of the graph (not a fluid line). As stated before, it is cheaper to have few large units than many small units.

Table 6.3 Costs per tonne MSW combusted with or without evaporation of the waste water (explanation in text)

Plant capacity [ktonnes per year]	**Cost per tonne MSW *without* waste water evaporation [ECU per tonne]**	**Cost per tonne MSW *with* waste water evaporation [ECU per tonne]**
63	229	279
105	184	231
189	145	187
294	122	160
399	108	145
505	99	134
617	97	129
701	92	125
806	92	124

In order to make clear how these processing costs are built up the costs for an annual capacity of 505,000 tonnes per year are specified below. All costs, except the final cost per tonne are expressed as millions ECU per year.

Processing costs

	Waste water evaporation	
Item	*without*	*with*
Capital costs	36.8	48.9
Operational costs		
- personel	3.5	3.5
- maintenance electro/mechanical	9.0	12.5
- maintenance building/construction	0.4	0.4
- insurances	2.1	2.9
- emission measurements[1]	0.3	0.3
- plant vehicles [2]	0.6	0.6
- chemicals/utilities [3]	1.5	0.8
- disposal costs [4]3.0	3.9	
Total operational costs	20.2	24.7
Electricity sales revenue [5]	7.3	6.1
Total costs per year	49.8	67.5
MSW combusted per year [ktonnes]	505	505
Cost per tonne MSW [ECU/tonne]	99	134
	===	====

6.2 Retrofitting existing facilities

Existing MSW combustion facilities can be retrofitted in order to fulfill the emission requirements of the EC Directive on HWC, as it was described in chapter 3. Depending on the already installed flue gas cleaning system a number of measures would have to be taken as shown in table 3.1. In this chapter first the investment costs for the retrofitting are calculated and after that the extra cost per tonne MSW, caused by the retrofitting.

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[1] Depending on the guideline a fixed number of times per year the emissions have to be checked with the permit. This must be done by an external company. These costs are based on measurements as required by the Dutch guideline (see chapter 4.3).

[2] The vehicles meant here are used for transporting the solid residues (bottom-ash, fly-ash, etc.) on the plants' site.

[3] The waste water which is evaporated is condensed and used again in the scrubber. Through this the amount of fresh water used can be reduced which results in a cost saving as shown.

[4] Through evaporation of the waste water a solid residue (salts) is produced, which needs to be landfilled. This results in increased disposal costs.

[5] The waste water evaporation uses up steam, which then cannot generate electricity anymore: thus, less electricity is produced than without evaporation of the waste water. Besides this the evaporation unit uses up an amount of electricity (pumping, etc.). Therefore with waste water evaporation less electricity can be sold per tonne waste.

In order to be able to make these calculations numerous assumptions have to be made and the situations have to be generalised. Some of the assumptions might be not true for all the installations but have to be made in order to keep the calculations within reasonable complexity.
The accuracy of the resulting costs therefore should not be overestimated and should be considered to be **indicative, not exact**.

As a base for the calculations the costs for new equipment parts, as described in chapter 6.1, are used. Items which are already installed are left out and only the changes towards the existing situation are counted. This implies that for installation parts which are already present or utilities of which less is used up, a cost has to be deducted. For example, if there is already a dust removal device present, not only the investment costs for the ESP have to be left out, but also the investment for the building/construction part decreases. In the same way it is possible that the extra cost through retrofitting are negative for a certain part, just because after retrofitting the plant uses less of a certain chemical or utility, than before retrofitting. Always the amount used in the existing situation is subtracted from the amount used after retrofitting.

The following assumptions refer to all the flue gas cleaning categories:
- no costs are considered for special, local circumstances;
- half the investment costs for buildings (see chapter 6.1) are considered to concern the flue gas cleaning system;
- retrofitting does not require extra investment costs for the infrastructure, the energy generation, the stack, the slag treatment, the shredder, the grate or the boiler;
- always a new fan has to be installed;
- none of the required emission measurement equipment is already present;
- retrofitting does not change the costs for personel or for plant vehicles.

Furthermore per flue gas cleaning category assumptions were made. These are presented per category. In all the categories which are retrofitted with, or already have a wet scrubber (1- or 2-staged), the costs are presented with and without evaporation of the waste water. The consequences for the costs are the same as for new MSW combustion facilities (see chapter 6.1.1 and 6.1.2). It is assumed that none of the existing installations have a waste water evaporation already installed. In relation to a system without waste water evaporation a system with evaporation:
- has lower water costs, because the evaporated water is condensed and used again;
- has lower revenues from the sale of electricity, because they produce less electricity (steam partly used for evaporation), and consume more (evaporator);
- has higher investment costs because of the (consderable) investment of the evaporator; this is slightly corrected by the lower investment for the turbine/generator, which has to process less steam and therefore can be smaller;
- has higher disposal costs since the solid salts residue has to be landfilled.

Flue gas cleaning category:

a Without flue gas cleaning

As stated in chapter 3 the installations in this category are retrofitted with an ESP, a 2-staged wet scrubber, a waste water treatment installation with or without waste water evaporation and an entrained flow adsorber (injection of an active coal/ $Ca(OH)_2$ mixture before a bag filter).

All the investment costs for the flue gas cleaning equipment are included and so are all the costs for chemicals, utilities and disposal costs.

b Only dust removal

The installations in this category are retrofitted with a 2-staged wet scrubber, a waste water treatment installation with or without waste water evaporation and an entrained flow adsorber.
Extra investment costs:
- no investment costs for the ESP;
- lower investment for building/construction than if no flue gas cleaning system was present.

Extra processing costs:
- no electricity consumption cost for the ESP, since the amount used by the ESP is also spent in the existing installation (no extra cost);
- no disposal costs for fly-ash (already in existing plant).

c.1 Dry scrubber, option 1): improved additive injection

In this option it is assumed that the dry scrubber, after improvement and with addition of special additives is capable of reducing the emissions to the required level (see also chapter 3). The improvement of the scrubber consists of improving the dust collection through relative humidity control, special hopper design and accurate bag filter control. Besides this the cokes handling and storage system has to be installed (high safety demands because of explosion or self-ignition risks).
Assumptions:
- the stoichiometry for the adsorbent has to be increased from 2 to 4: this also leads to increased disposal costs;
- the changes do not affect the electricity production or consumption.

c.2 Dry scrubber, option 2): scrubber is replaced by a 2-staged wet scrubber

In this option it is assumed that the dry scrubber will be replaced by a wet scrubber. The dust collection equipment can be used again so there is no investment for the ESP. The dry scrubber cannot be used again. Thus this installation is retrofitted with a 2-staged wet scrubber, a waste water treatment installation with or without waste water evaporation and an entrained flow adsorber.
Investment costs:
- no investment costs for the ESP;
- lower investment for building/construction than if no flue gas cleaning system was present.

Extra processing costs:
- no electricity consumption cost for the ESP, since the amount used by the ESP is also spent in the existing installation (no extra cost);
- the electricity consumption is corrected for the fact that in the existing installation the dry scrubber used up a certain amount;
- no disposal costs for fly-ash (already in existing plant);
- after retrofitting less $Ca(OH)_2$ is used since the stoichiometry for adsorption and neutralisation of the acid gases drops from 2 to 1.2: this also means a saving on disposal costs of the residues.

d.1 Semi-dry scrubber, option 1): improved additive injection

The same as with the dry scrubber, it is assumed in this option, that the semi-dry scrubber, after improvement and with addition of special additives is capable of reducing the emissions to the required level (see also chapter 3). The improvement of the scrubber consists of improving the dust collection through relative humidity control, special hopper design and accurate bag filter control. Besides this the cokes handling and storage system has to be installed (high safety demands because of explosion or self-ignition risks).

Assumptions:
- the stoichiometry for the adsorbent has to be increased from 1.8 to 3: this also leads to increased disposal costs;
- the changes do not affect the electricity production or consumption.

d.2 Semi-dry scrubber, option 2): scrubber is replaced by a 2-staged wet scrubber

In this option it is assumed that the semi-dry scrubber will be replaced by a wet scrubber. The dust collection equipment can be used again so there is no investment for the ESP. The semi-dry scrubber cannot be used again. In some cases it seems to be possible to reuse the semi-dry scrubber as a spray dry adsorber and thus evaporating the waste water. If this is possible this would be a cheaper way of evaporating the waste water than through separate evaporation. However, as this is not always possible this is not consideed here as general practice.

Thus this installation is retrofitted with a 2-staged wet scrubber, a waste water treatment installation with or without waste water evaporation and an entrained flow adsorber.

Investment costs:
- no investment costs for the ESP;
- lower investment for building/construction than if no flue gas cleaning system was present.

Extra processing costs:
- no electricity consumption cost for the ESP, since the amount used by the ESP is also spent in the existing installation (no extra cost);
- the electricity consumption is corrected for the fact that in the existing installation the semi-dry scrubber used up a certain amount;
- no disposal costs for fly-ash (already in existing plant);
- after retrofitting less $Ca(OH)_2$ is used since the stoichiometry for adsorption and neutralisation of the acid gases drops from 1.8 to 1.2: this also means a saving on disposal costs of the residues.

e. Wet scrubber, 1-stage:

Installations in this category are extended with a second stage for the wet scrubber, an expanded waste water treatment, optional waste water evaporation and an entrained flow adsorber.

Investment costs:
- no investment costs for the ESP;
- reduced investment costs for the wet scrubber;
- reduced investment costs for the waste water treatment system (not for the evaporation);
- lower investment for building/construction than if no flue gas cleaning system was present.

Extra processing costs:
- no electricity consumption cost for the ESP and a reduced consumption for the scrubber and the waste water treatment installation, since the amount used by this equipment parts is also spent in the existing installation (no extra cost);
- no disposal costs for fly-ash (already in existing plant);
- no cost for the consumption of additives in the water treatment installation;

- reduced disposal costs for the residues from the scrubber (sludge);
- only costs for the water and $Ca(OH)_2$ used in the second stage.

f. Wet scrubber, 2-staged:
These installations are extended with just an entrained flow adsorber and an optional waste water evaporation.
Investment costs:

- no investment cost for ESP, wet scrubber or waste water treatment installation;
- lower investment for building/construction than if no flue gas cleaning system was present.

Extra processing costs:

- no electricity consumption cost for the ESP, the wet scrubber and the waste water treatment installation, since the amount used by this equipment parts is also spent in the existing installation (no extra cost);
- no disposal costs for fly-ash and sludge (already in existing plant).

The installations which already have an active coal adsorption unit are assumed to fulfill the requirements of the EC Directive and are not retrofitted.

With all the assumptions per category the investment costs and the cost per tonne MSW were calculated for different capacities. These results were interpolated, in order to be able to calculate quickly the costs for every capacity. The results are presented in figures 13 and 14 for the investment costs and in figures 15 and 16 for the extra costs per tonne MSW combusted. In table 6.4 the figures are presented.

Table 6.4 Investment costs and extra cost per tonne for retrofitting existing MSW combustion facilities with different flue gas cleaning and different capacities

Capacity [kton/yr]	63	105	189	294	399	505	617	701	806
number of units	3	3	3	3	3	3	4	4	5
	Investment costs [MECU] per category								
a. no flue gas cleaning									
- without water evaporation	36.1	48.2	67.4	87.3	104.5	120.1	143.4	154.7	176.1
- with water evaporation	56.4	79.1	117.8	159.9	197.8	233.0	276.3	302.1	341.0
b. only dust removal									
- without water evaporation	30.5	40.5	56.1	72.4	86.5	99.2	117.9	127.1	144.1
- with water evaporation	50.8	71.4	106.6	145.0	179.8	212.2	250.7	274.5	309.0
c. dry scrubber									
c.1. extra additives	7.2	8.0	9.4	10.8	11.9	13.0	16.6	17.4	21.0
c.2. replaced by wet scrubber									
- without water evaporation	30.5	40.5	56.1	72.4	86.5	99.2	117.9	127.1	144.1
- with water evaporation	50.8	71.4	106.6	145.0	179.8	212.2	250.7	274.5	309.0
d. semi-dry scrubber									
d.1. extra additives	7.2	8.0	9.4	10.8	11.9	13.0	16.6	17.4	21.0
d.2. replaced by wet scrubber									
- without water evaporation	30.5	40.5	56.1	72.4	86.5	99.2	117.9	127.1	144.1
- with water evaporation	50.8	71.4	106.6	145.0	179.8	212.2	250.7	274.5	309.0
e. wet scrubber, 1-stage									
- without water evaporation	22.4	29.2	40.0	51.2	60.9	69.7	83.6	90.0	102.8
- with water evaporation	42.6	60.1	90.4	123.8	154.2	182.7	216.4	237.4	267.7
f. wet scrubber, 2-staged									
- without water evaporation	10.8	13.1	16.9	20.9	24.2	27.3	33.8	36.2	42.5
- with water evaporation	31.0	44.0	67.3	93.4	117.5	140.2	166.7	183.5	207.4
	Extra cost per tonne [ECU/ton]								
a. no flue gas cleaning									
- without water evaporation	125	101	80	68	61	56	55	53	52
- with water evaporation	191	162	135	119	109	103	100	97	95
b. only dust removal									
- without water evaporation	104	82	64	53	47	44	43	41	40
- with water evaporation	170	143	119	105	96	90	88	85	83
c. dry scrubber									
c.1. extra additives	33	24	18	15	13	12	12	12	12
c.2. replaced by wet scrubber									
- without water evaporation	98	77	58	48	42	38	37	35	35
- with water evaporation	164	138	114	99	91	85	82	79	78
d. semi-dry scrubber									
d.1. extra additives	31	22	15	12	11	10	10	10	10
d.2. replaced by wet scrubber									
- without water evaporation	99	77	59	49	43	39	38	36	35
- with water evaporation	165	138	114	100	91	85	83	80	78
e. wet scrubber, 1-stage									
- without water evaporation	75	58	44	36	32	29	28	27	27
- with water evaporation	141	119	99	87	80	76	73	71	70
f. wet scrubber, 2-staged									
- without water evaporation	38	27	19	15	13	11	11	11	11
- with water evaporation	105	88	74	66	61	58	57	55	54

6.3 Calculating the total investment and extra cost per tonne for Europe

With the information on the cost of retrofitting existing installations and the data on the MSW combustion facilities in Europe a total estimate can be made of the investment cost and the extra cost per tonne which would have to be payed if all the installations were retrofitted to the level of the EC Directive on HWC. Then these costs can be related to the emission reduction which the retrofitting of all the facilities would render.

However, such a calculation would only give an indication and must not be seen as an exact figure (see also the previous chapter).

In table 6.5 the results of this calculation are shown. It was assumed that the installations, of which the flue gas cleaning system is unknown, have no flue gas cleaning equipment at all. The total investment is calculated by adding up all the investments for all the installations, whereas the extra cost per tonne is a (weighed) average for all the installations. In table 6.5 4 situations are considered, because there are two factors which have two options: what happens to the dry and semi-dry scrubber and is the waste wtaer evaporated. The 4 situations are:

- the dry/semi-dry scrubbers are **not** replaced, the waste water is **not** evaporated;
- the dry/semi-dry scrubbers are replaced, the waste water is **not** evaporated;
- the dry/semi-dry scrubbers are **not** replaced, the waste water is evaporated;
- the dry/semi-dry scrubbers are replaced, the waste water is evaporated.

Like with the total emission per country (table 5.2) the total investment per country does not give a true picture of the level of the existing installations in a certain country: the amount of waste which is combusted needs to be taken into account for that. Therefore in the second part of the table the investment is expressed per tonne of waste. The difference between these two approaches can be seen when the figures for Finland are compared: the total investment is low but the investment per tonne MSW is high. The latter approach (investment per tonne) is more realistic since the investment has to be paid back by combusting tonnes.
Countries which need to invest relatively much per tonne before the emissions as in the EC Directive on HWC can be realised, are France, Italy, Norway, Finland and the United Kingdom. Relatively low investments per tonne are required in Austria, Germany and the Netherlands.
On average the extra processing costs, for Europe as well as for the EC, are 52 to 144 ECU, depending on the situation.

Looking at the absolute figure for the investments you can see that an enormous amount of money (14 to 30 GECU, 1 GECU = 1,000,000,000 ECU) would be involved if all the installations would be retrofitted. On top of that there will also be investments for new installations, which have to be added to this total. However, as is indicated in Appendix A, not all the MSW facilities would be retrofitted: a lot of the existing installations will be shut down in the nearby future. The facilities in the EC member countries have to comply with the EC Directive (from 1989) by 1996 (a few years later for small facilities, see chapter 4.3). Though this Directive is not nearly as strict as the Directive on HWC, a lot of installations will be shut rather than be retrofitted. In general the smaller installations are shut first, because retrofitting is relatively more expensive as the installation is smaller. As small installations need relatively high investments (per tonne MSW), this can considerable lower the remaining amount, which still has to be invested.

Table 6.5 Investment costs per country and per tonne of MSW and the extra cost per tonne because of retrofitting all the existing MSW faclities

	Investments [MECU]				Cost per tonne			
Waste water evaporation	without	without	with	with	without	without	with	with
Replacing dry/semi dry	no	yes	no	yes	no	yes	no	yes
A	0	0	0	0	0	0	0	0
B	788.6	898.1	1412.0	1633.2	65	73	114	132
CH	559.8	625.3	1418.5	1547.3	37	41	93	101
D	865.4	1676.8	2414.6	4159.1	17	29	44	72
DK	516.0	940.5	927.1	1761.6	38	67	66	127
E	529.4	529.4	860.6	860.6	91	91	151	151
F	7332.4	8034.4	11677.2	13031.8	89	98	141	160
I	1000.6	1053.2	1674.0	1770.9	92	96	151	159
L	8.7	50.5	8.7	95.6	18	64	18	120
N	481.5	481.5	803.6	803.6	90	90	155	155
NL	181.1	211.9	449.7	509.3	12	14	30	33
S	409.9	699.5	713.3	1297.3	43	68	71	126
SF	36.0	36.0	62.1	62.1	95	95	160	160
UK	1351.0	1351.0	2449.6	2449.6	74	74	132	132
Europe	14060.3	16588.1	24871.0	29981.9	52	61	93	114
EC	12573.1	14745.8	21873.5	26271.7	53	63	94	114
	Investment per tonne MSW [ECU/tonne]							
A	0	0	0	0				
B	351	400	629	728				
CH	197	220	500	545				
D	72	139	201	346				
DK	224	408	402	764				
E	715	715	1162	1162				
F	647	709	1030	1150				
I	527	555	882	934				
L	52	300	52	569				
N	958	958	1598	1598				
NL	58	67	143	162				
S	220	376	384	698				
SF	513	513	886	886				
UK	369	369	668	668				
Europe	326	385	577	695				
EC	335	393	583	700				

7 Conclusions

In this report the amount and composition of the municipal solid waste (MSW) is given for all the countries in Europe (EC member countries plus Switzerland, Austria, Norway, Sweden and Finland). Also the way this waste is processed is mentioned: landfill, combustion, recycling or composting.

For each country the MSW combustion installations are known including technical data like capacity, flue gas cleaning system and the way of energy recovery. The information is nearly complete: only for some installations in France, Italy and one in Spain, the applied flue gas cleaning technology is not known. Of the countries considered here, Ireland, Greece and Portugal do not have MSW combustion facilities.

The information on future development of the MSW combustion facilities (new plants, plants extended, retrofitted or closed) is scarce, uncertain and very fragmented. Due to public opposition the new facilities which are planned are not always built.

As an example of a state-of-the-art combustion facility the following process scheme is chosen:

- shredders (for bulky water);
- moving grate combustor;
- boiler, which produces steam, which is transformed into electricity;
- electrostatic precipitator;
- 2-staged wet scrubber with waste water treatment;
- waste water evaporation unit (optional);
- heat exchangers to reheat the flue gas;
- entrained flow adsorber (reactor with injection of a mixture of active coal and calciumhydroxide upstream a bag filter);
- a fan and a chimney.

For several (9) capacities in the range from 63,000 tonnes to 806,000 tonnes per year the investment costs and the costs per tonne for such a state-of-the-art MSW combustion facility are calculated. If the waste water does not have to be evaporated, the investment for new MSW combustion faclities varied from 90 millions ECU to 500 millions ECU for these capacities. The processing costs per tonne range from 279 ECU per tonne (63,000 tonnes per year) to 92 ECU per tonne (806,000 tonnes per year). With waste water evaporation the required investments increase to 110 millions ECU for a capacity of 63,000 tonnes per year and 660 millions ECU for a capacity of 806,000 tonnes per year. Processing costs then become respectively 279 and 124 ECU per tonne.

Adapting all the existing installations to the EC Directive on HWC would decrease the emissions of dust, HCl, HF and PCDD/F to 1 or 2% of the present emission. The emissions of SO_2, Hg, Cd and other heavy metals thus are reduced to respectively 10, 19, 13 and 5% of the present emission.

The calculated emission reductions are based on the situation that all the existing MSW facilities are retrofitted such, that they can meet the emission demands of the

EC Directive on HWC. The investment costs for retrofitting all these facilities are 14 to 30 billion ECU. Transferred to the processing costs this means that retrofitting costs 52 to 114 ECU per tonne extra (on top of what had to be paid before retrofitting).

Within Europe there are at the moment enormous differences in the level of flue gas cleaning installed, and thus also in the emissions and retrofitting costs. Countries with relative high emissions also will have to invest the most per tonne of waste. From the countries considered in this study relatively high investment costs per tonne waste are required for France, Italy, Spain, Finland and the United Kingdom. The countries which have the lowest emissions and investment costs per tonne MSW are Austria, Germany and the Netherlands.

It appeared that the calculations required numerous assumptions. The results should therefore be considered as indicative and not as exact.

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9 Authentication

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

-

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

February 1992 - August 1993

Signature	Approved by
Ir. L.P.M. Rijpkema research coordinator	Ir. J. de Koning section leader

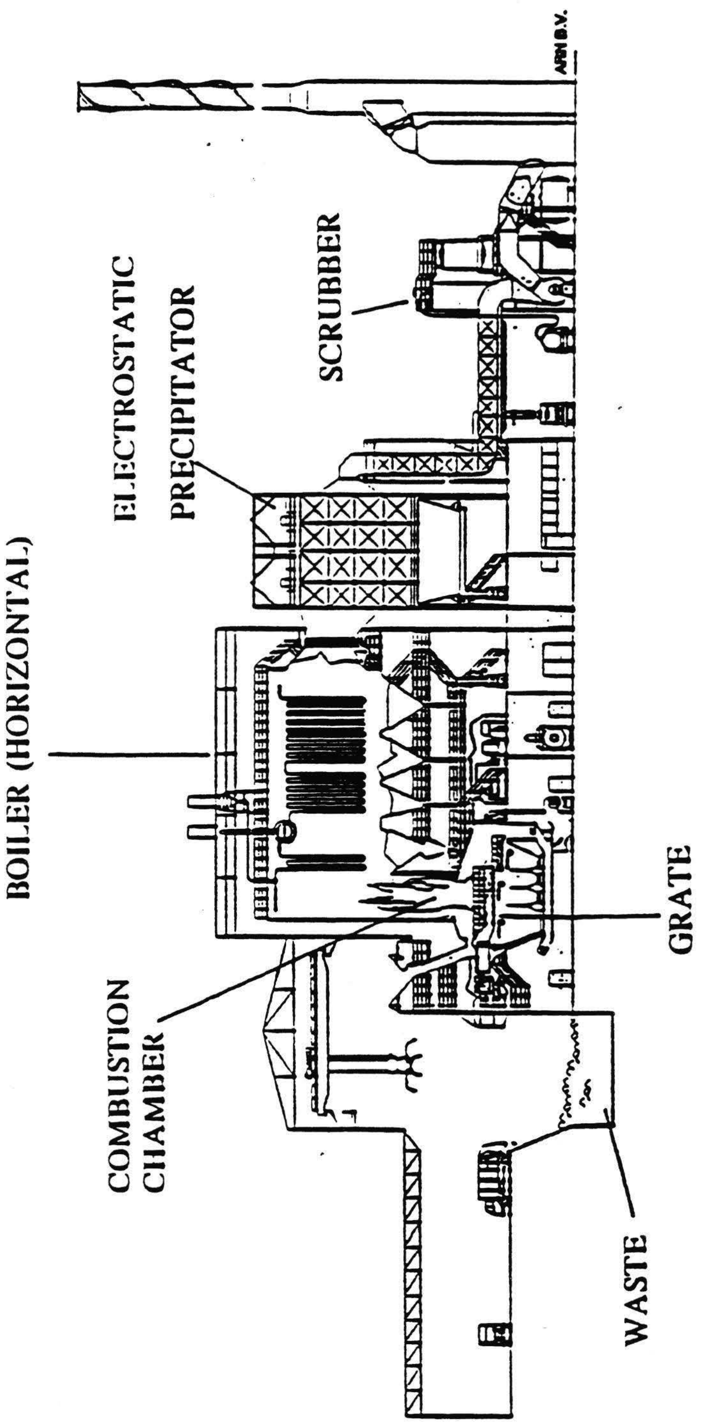


Figure 1 Municipal Solid Waste combustor (ARN BV, Nijmegen, NL)

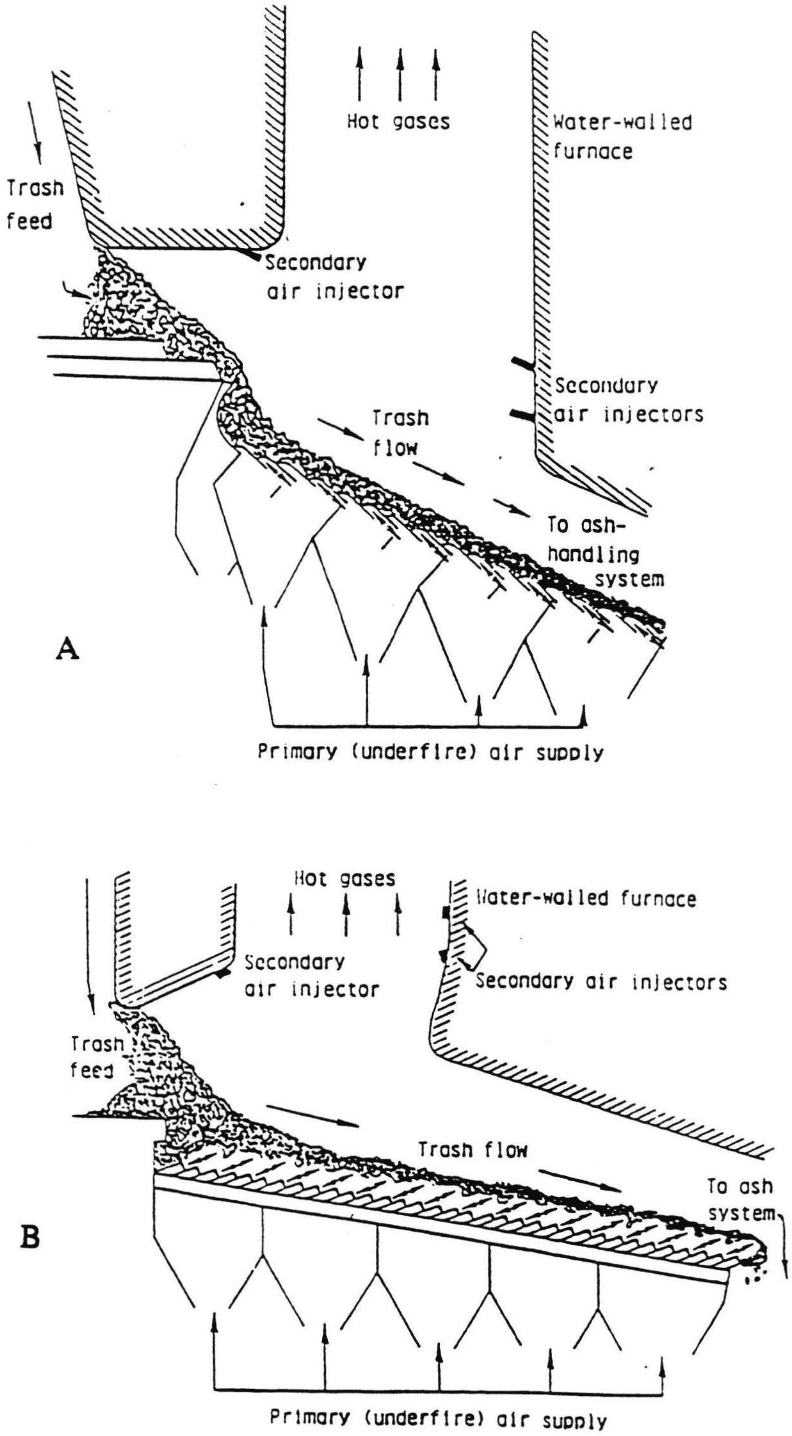


Figure 2 Different grate types; Forward (A) and reverse (B) acting reciprocating, Rotary drum grate (C) (taken from [Penner et al, 1987])

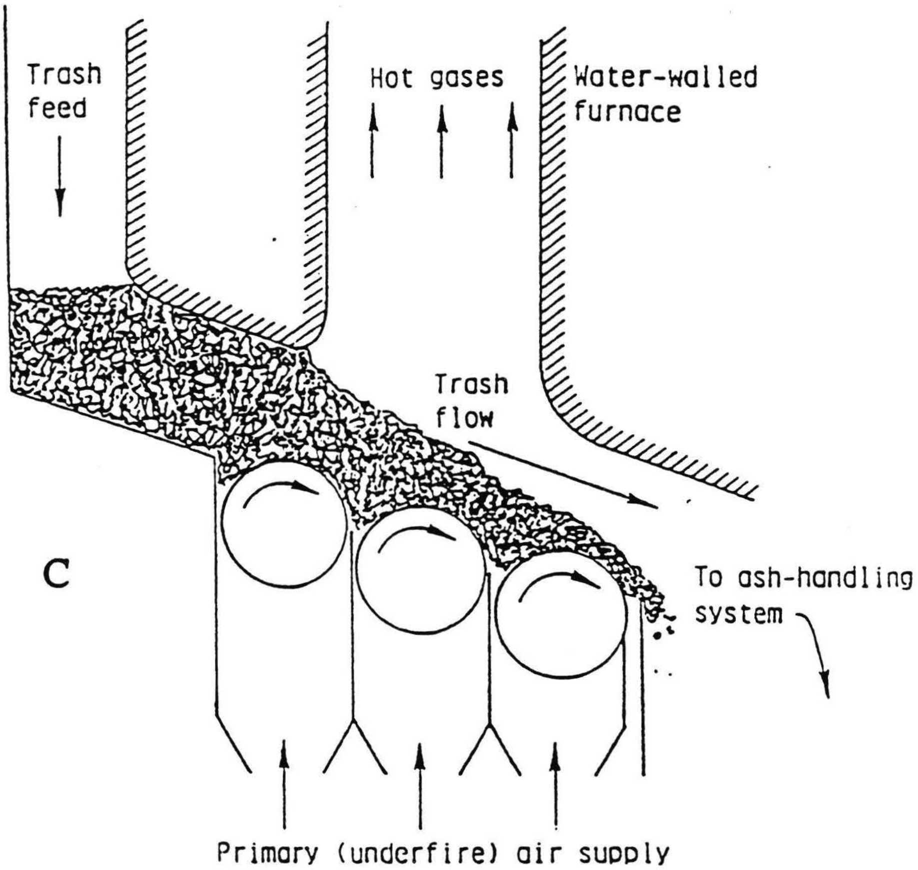


Figure 2.c Rotary drum grate

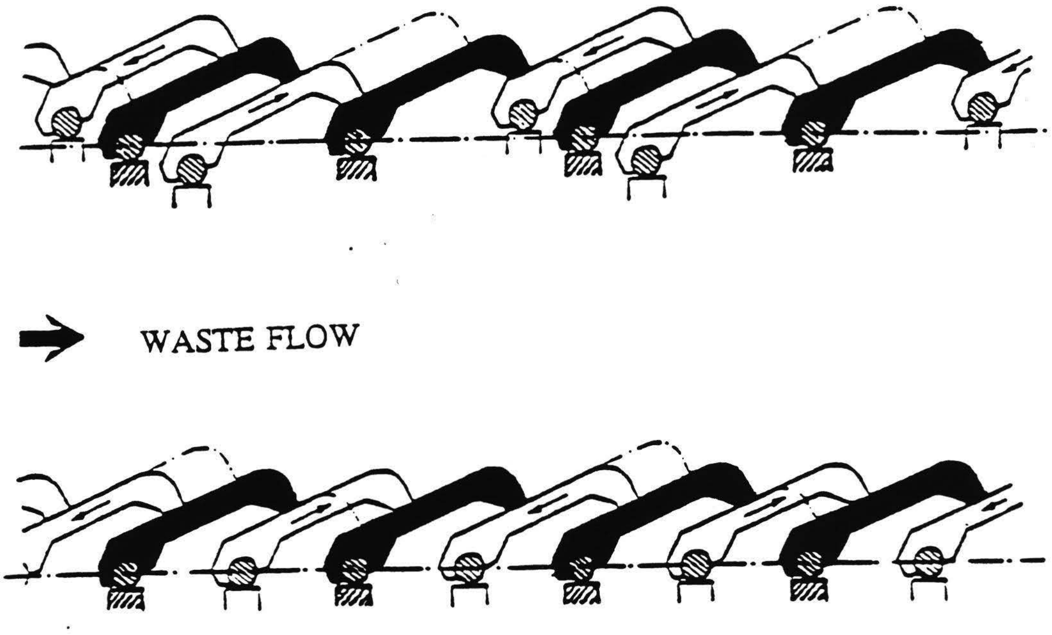
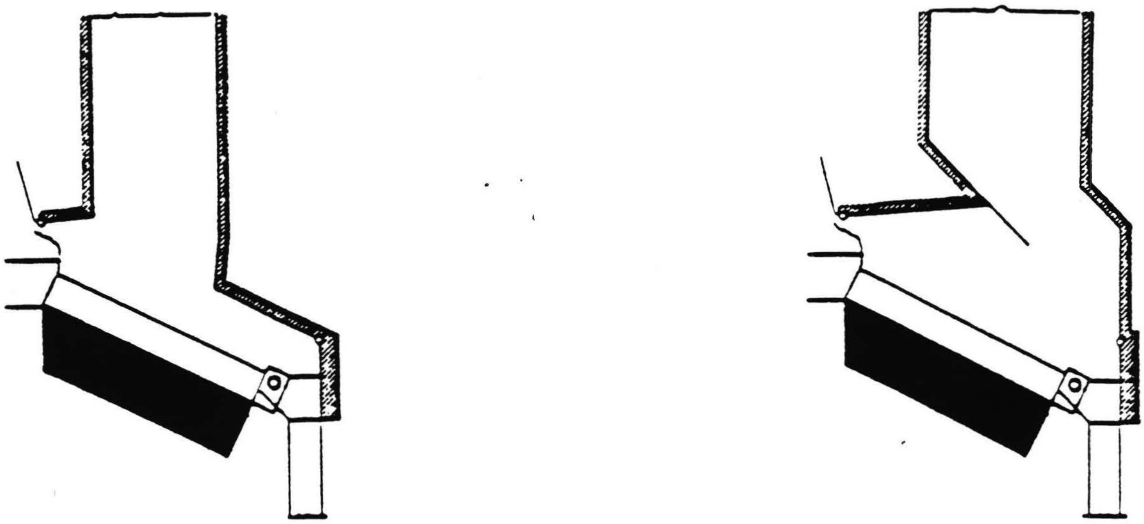
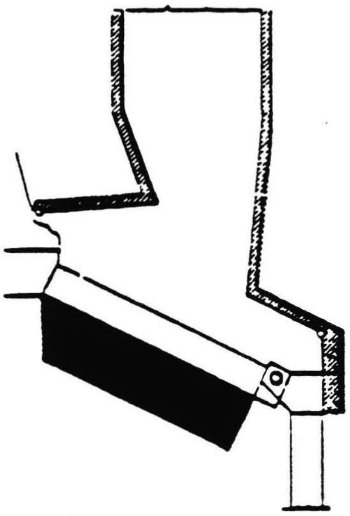


Figure 3 Forward and reverse acting reciprocating grate (taken from [Thome-Kozmiensky, 1983])



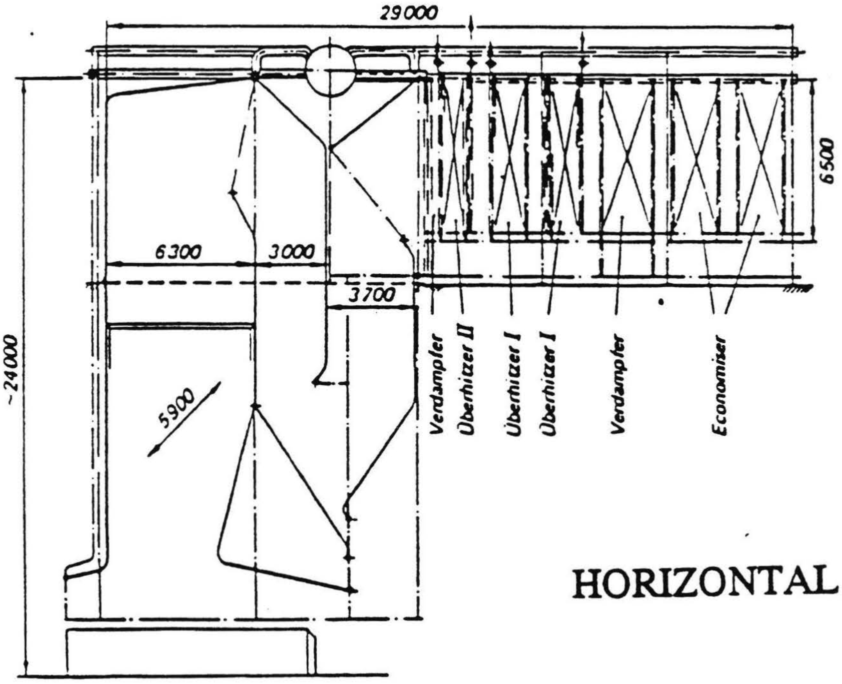
COUNTERFLOW

PARALLEL FLOW

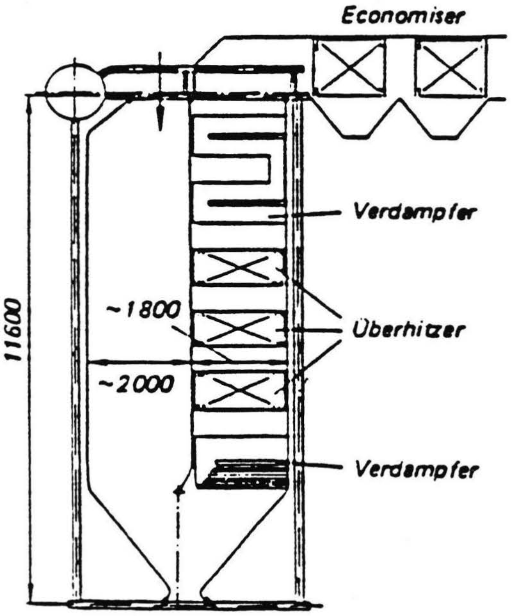


INTERMEDIATE FLOW

Figure 4 *Furnace geometries: countergflow, parallelflow and intermediate flow (taken from [Reimann, 1991b])*



HORIZONTAL BOILER



VERTICAL BOILER

Figure 5 Horizontal and vertical boiler (taken from [Schatz, 1991])

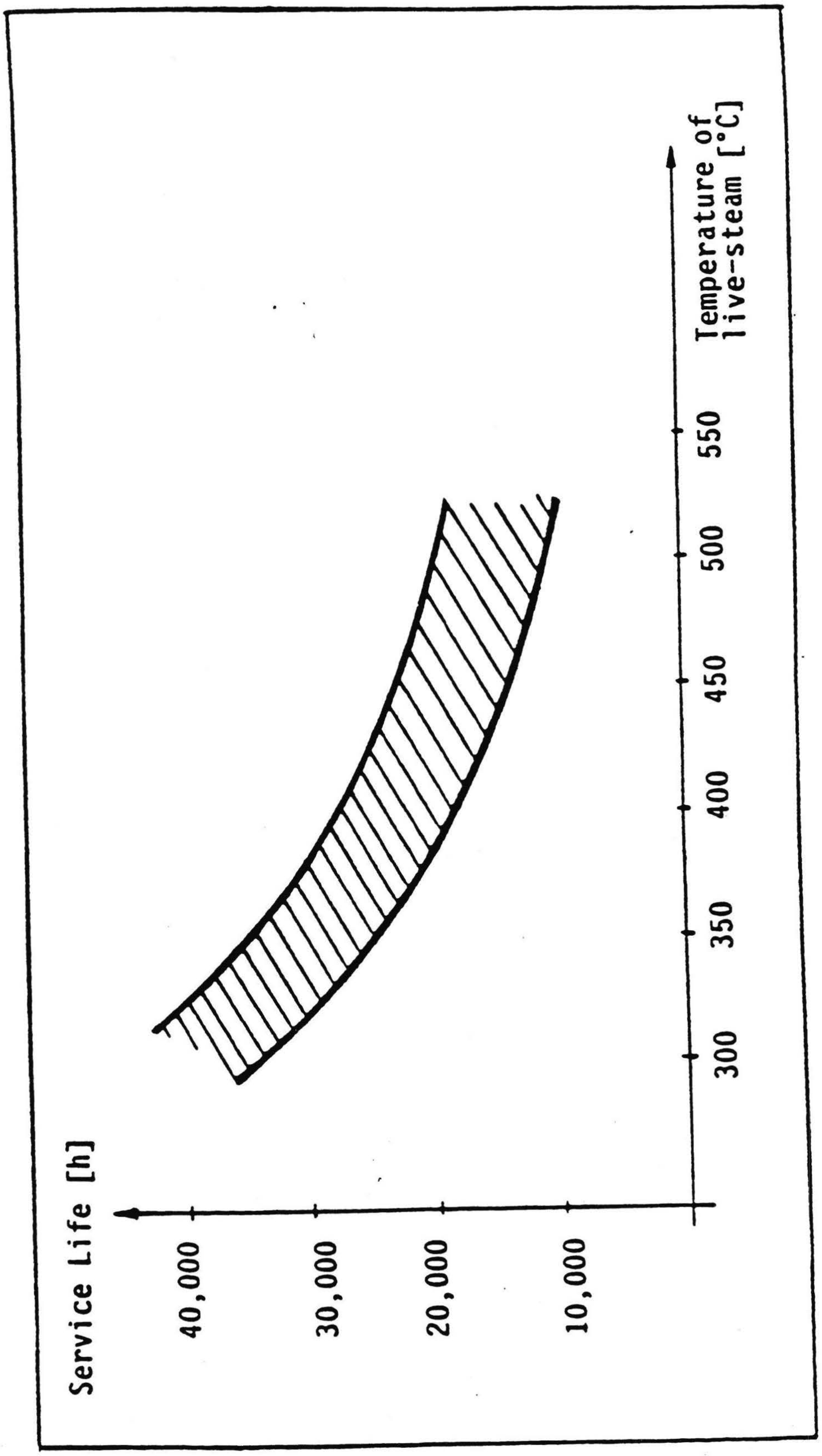


Figure 6 Lifetime versus steam temperature for a boiler (taken from [Barniske, 1990])

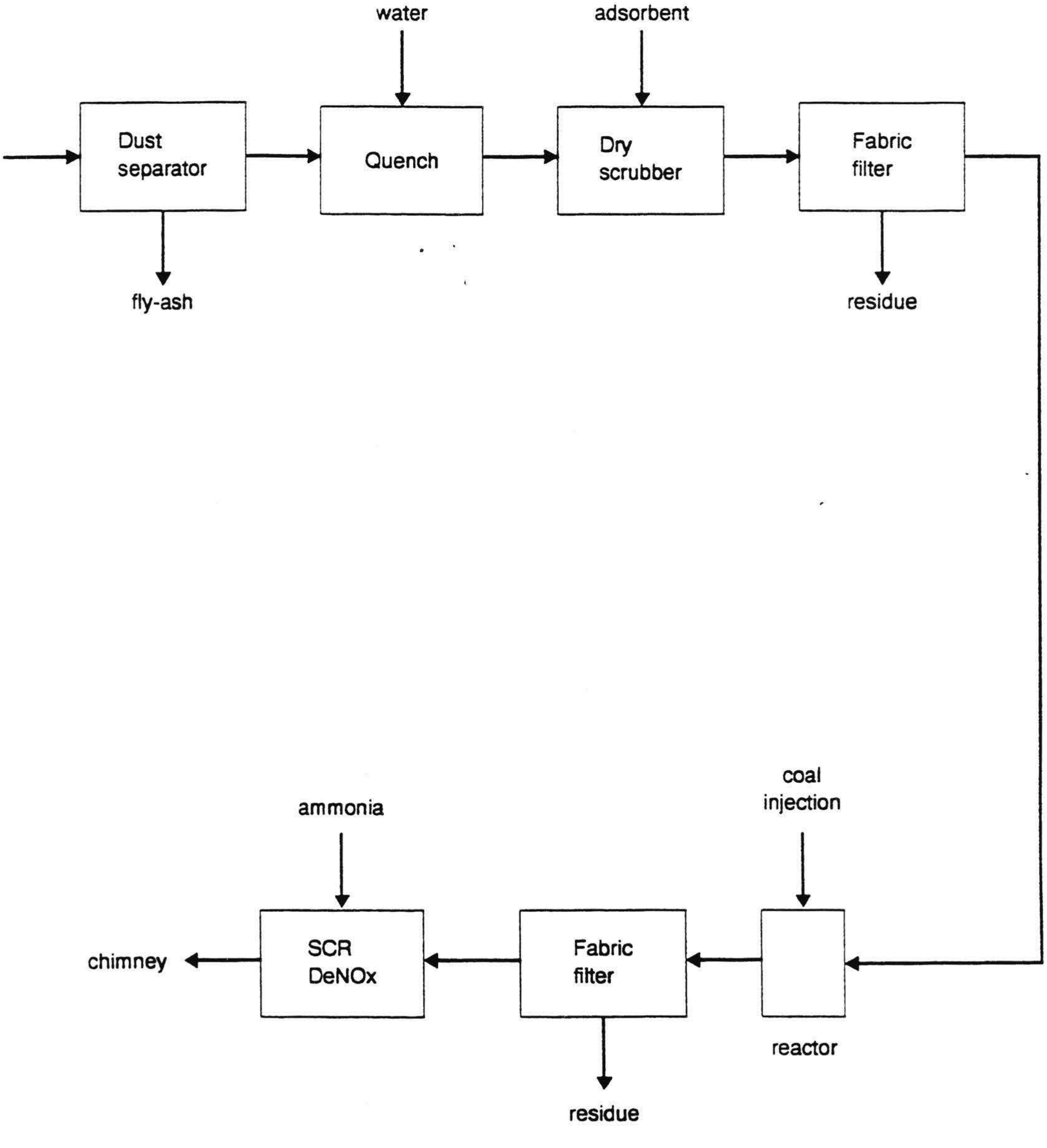


Figure 7 Block diagram of flue gas clenaing system with a dry scrubber

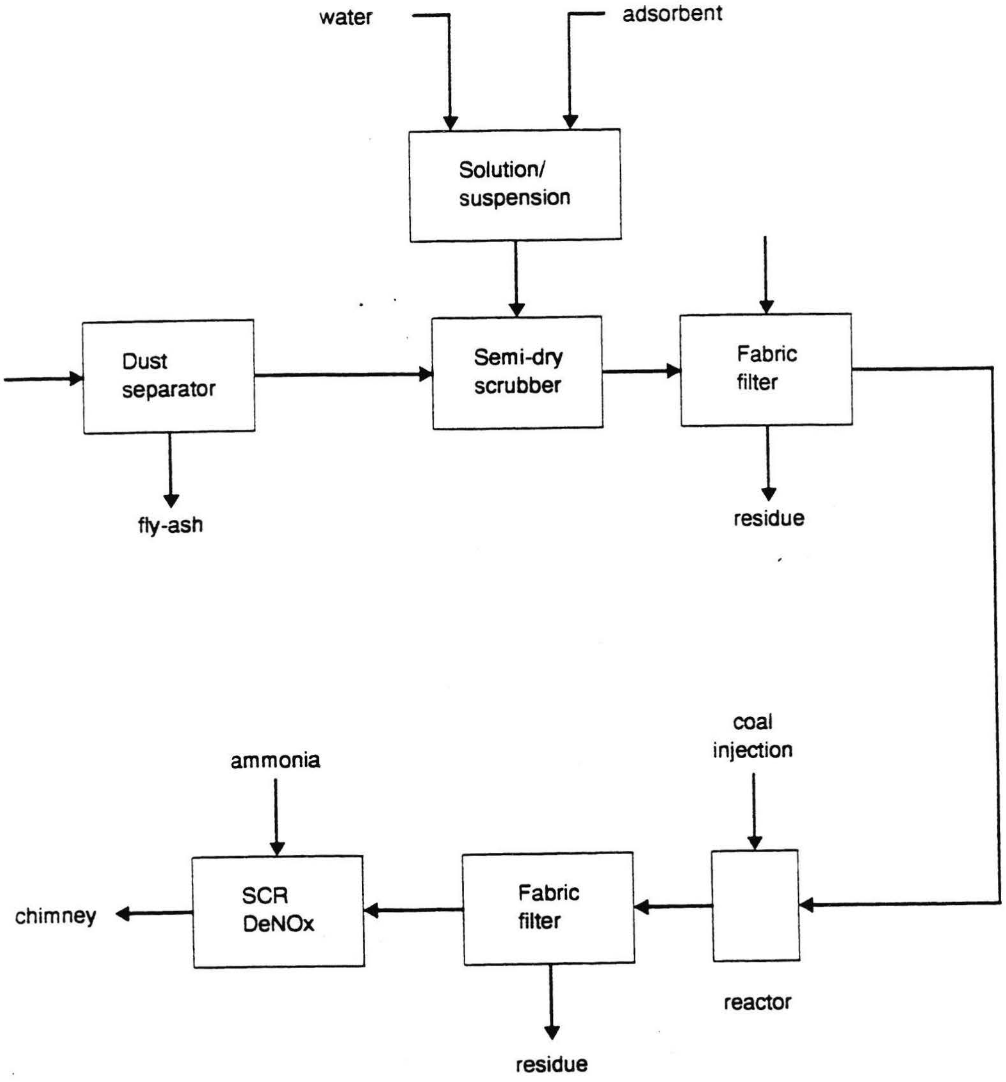


Figure 8 Block diagram of flue gas cleaning system with a semi-dry scrubber

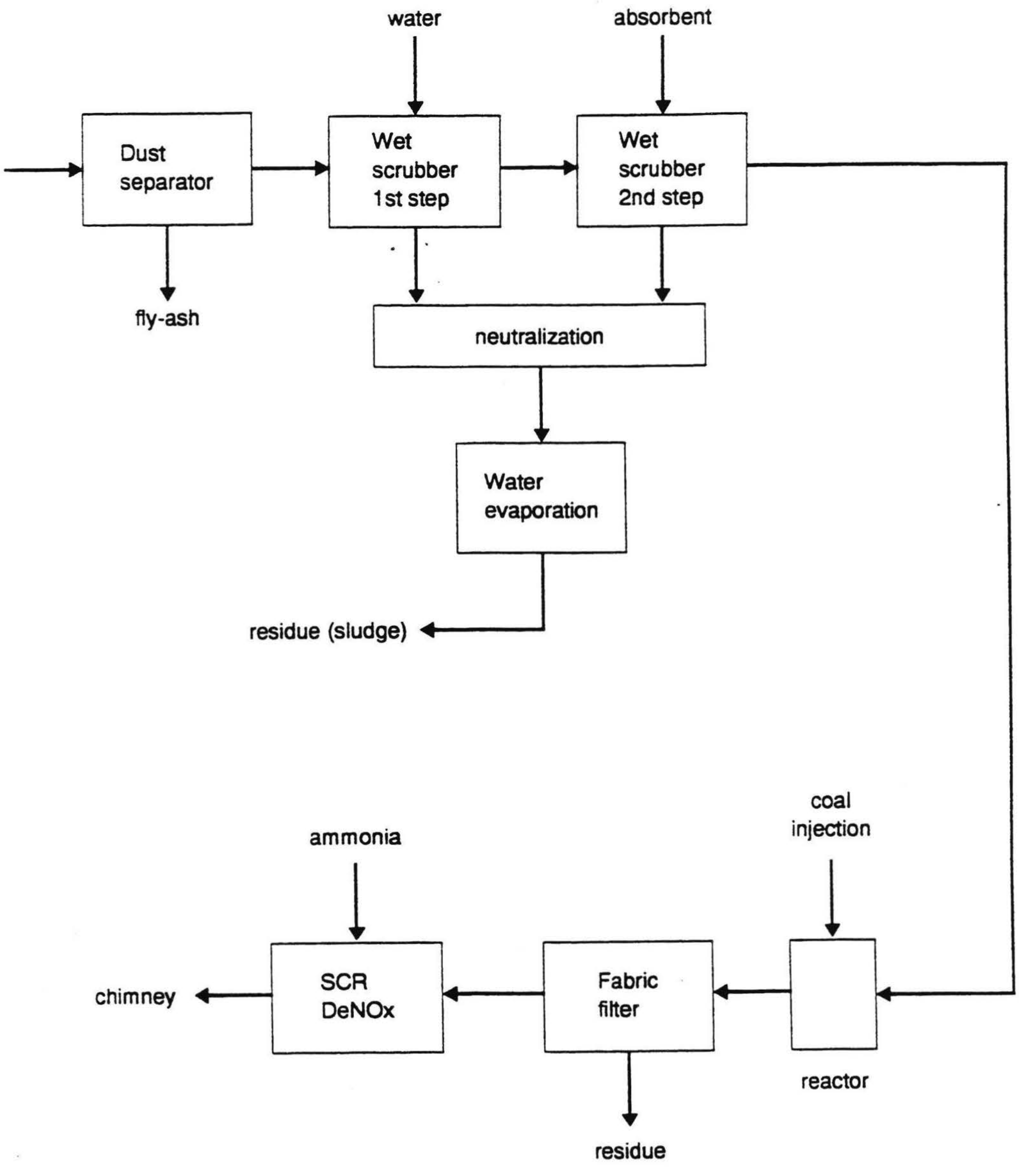


Figure 9   Block diagram of flue gas cleaning system with a wet scubber

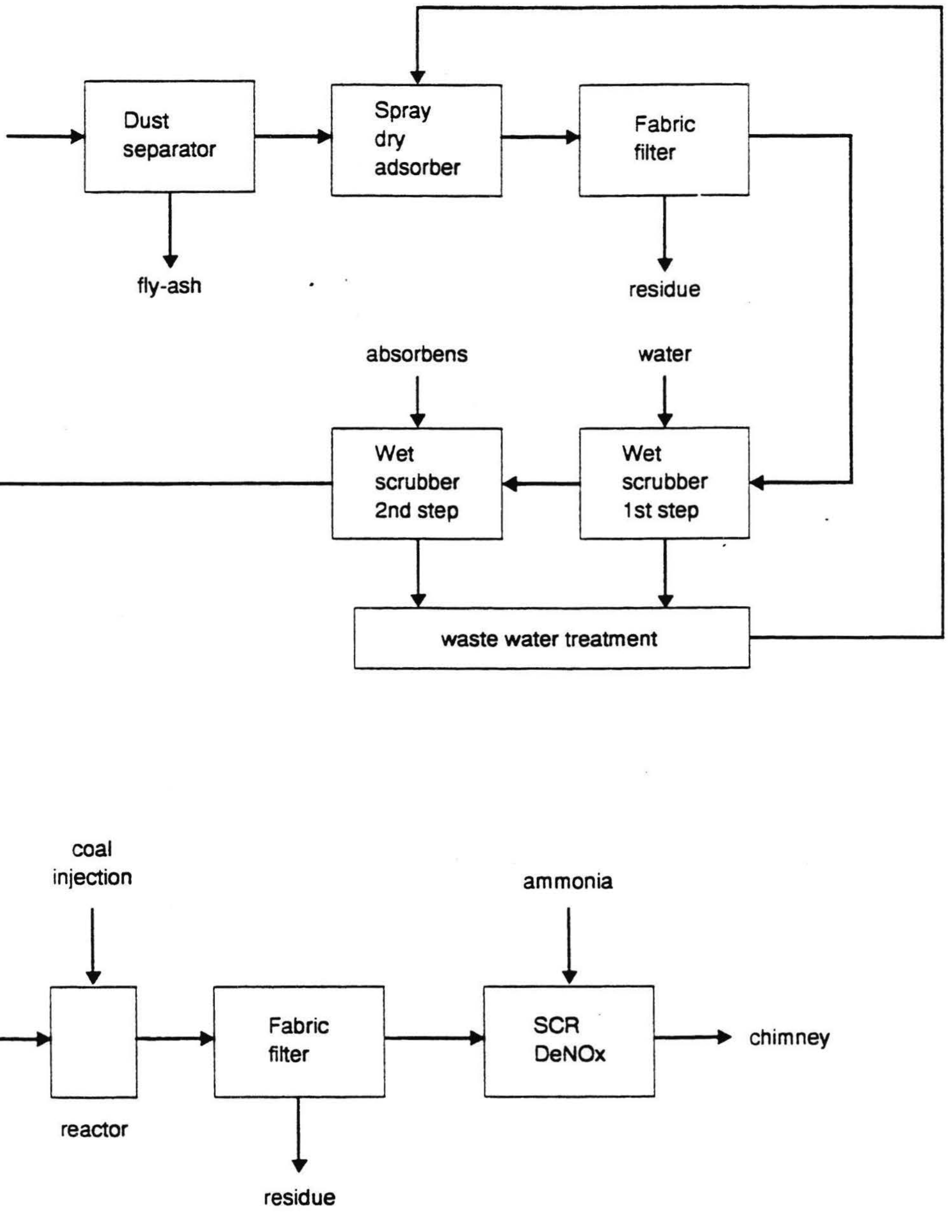


Figure 10 Block diagram of flue gas clenaing system with a wet scubber, with evaporation of the waste water in a spray dry adsorber

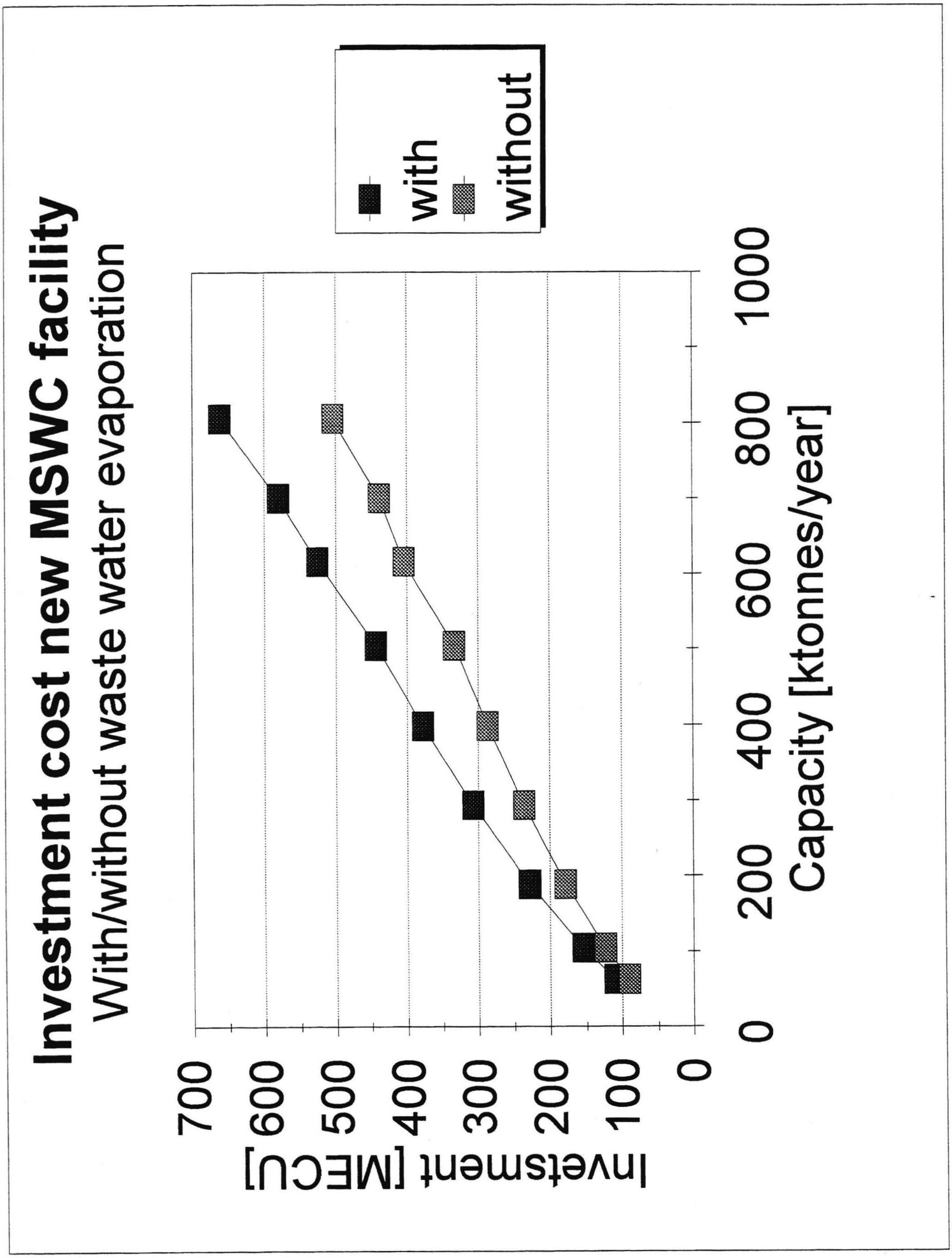


Figure 11 Investment costs for a new MSW combustion facility, with or without evaporation of the waste water

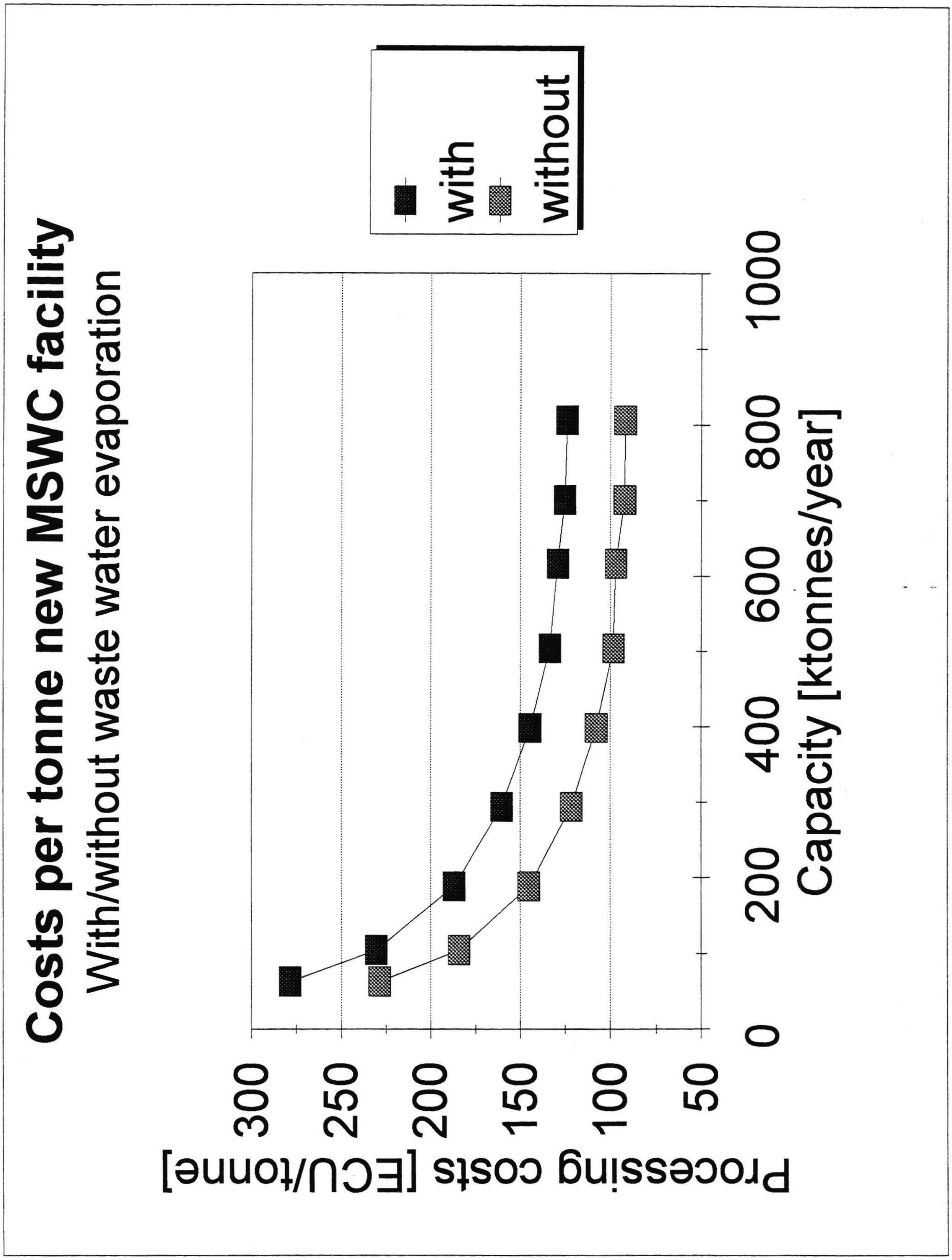


Figure 12 Costs per tonne MSW combusted in a new facility, with or without evaporation of the waste water

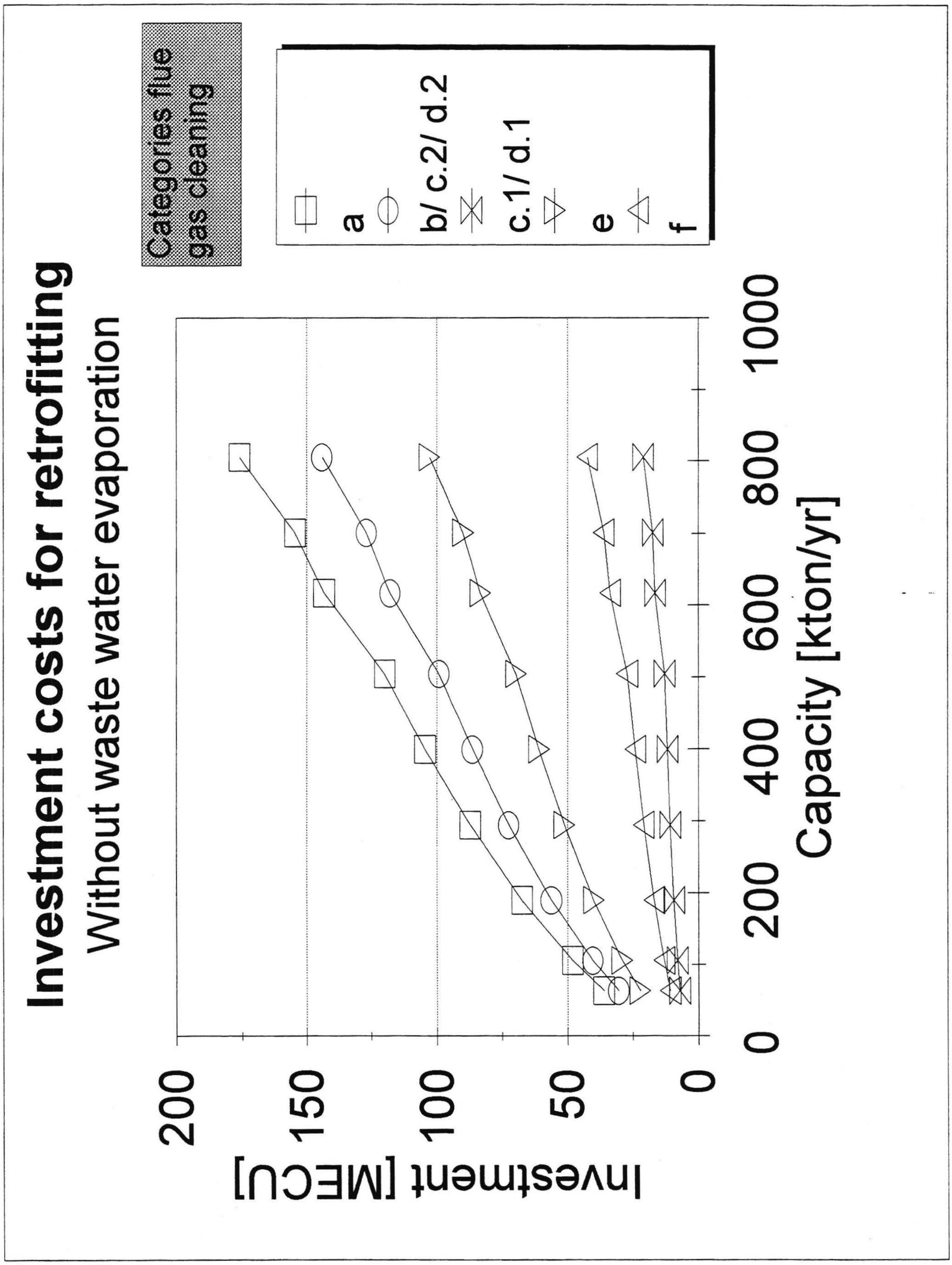


Figure 13 *Investment cost for retrofitting existing installations, including waste water evaporation, depending on the already existing flue gas cleaning system. (legend explained in table 6.4)*

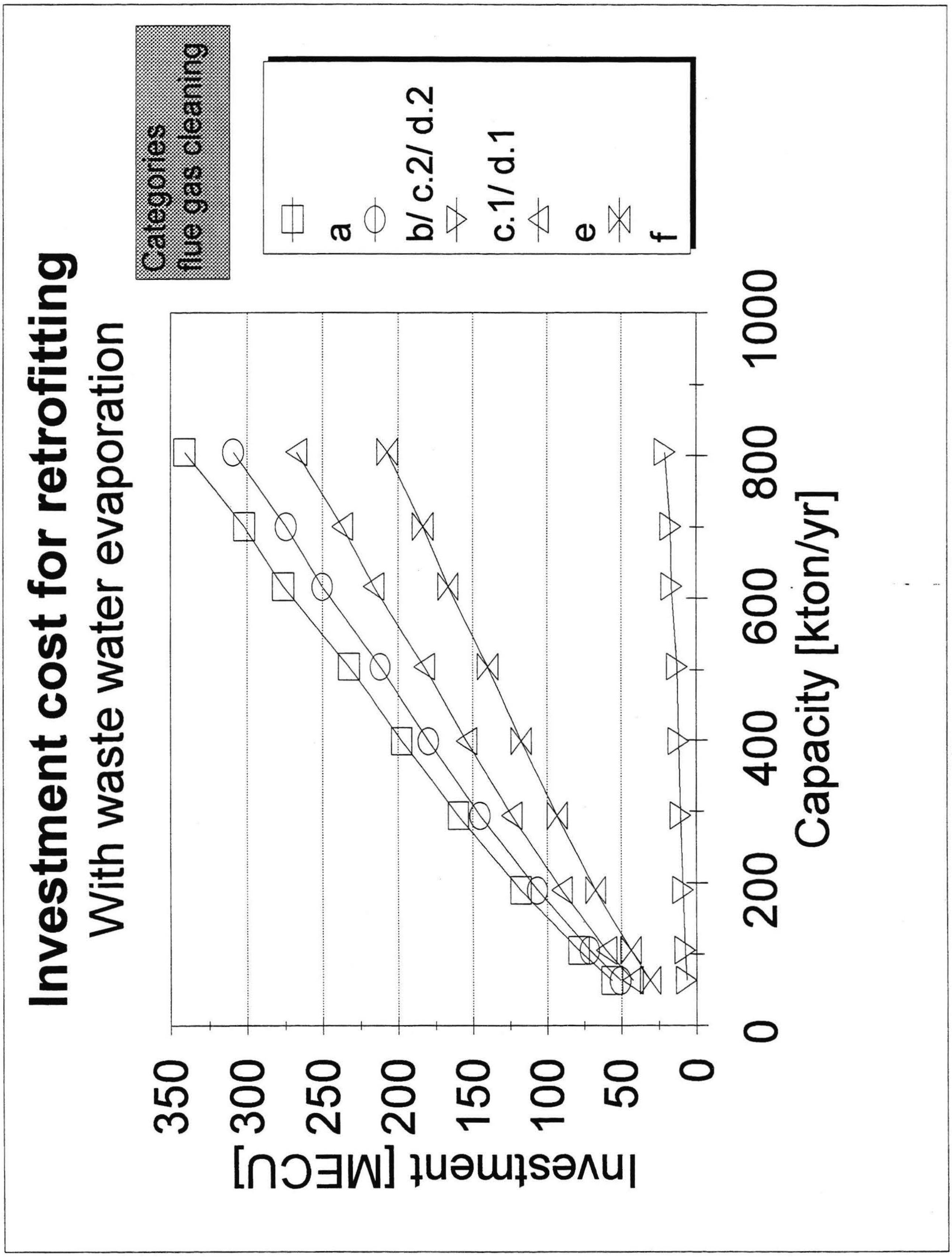


Figure 14 Investment cost for retrofitting existing installations, without waste water evaporation, depending on the already existing flue gas cleaning system (legend explained in table 6.4)

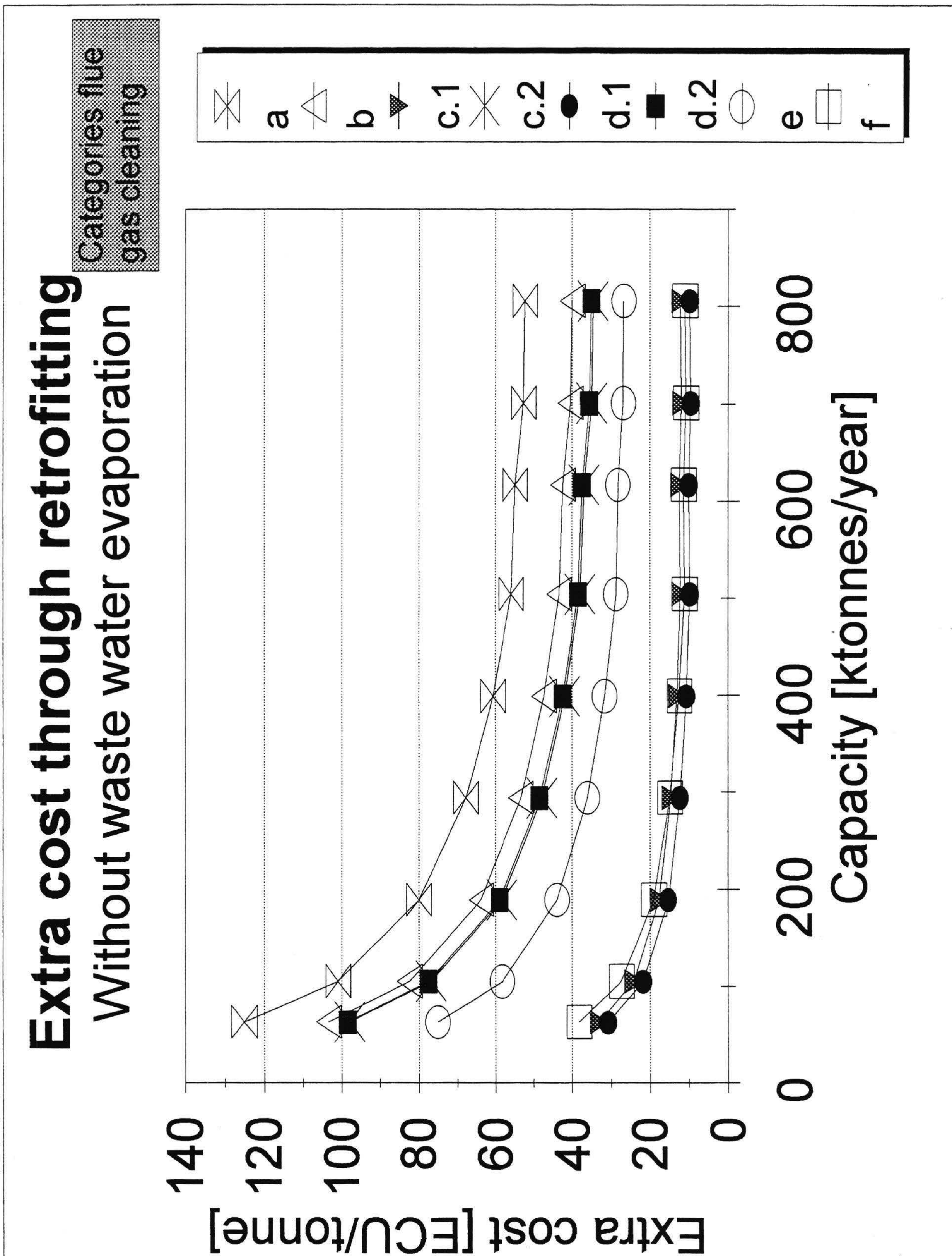


Figure 15 Extra cost per tonne MSW for retrofitting existing installations including waste water evaporation, depending on the already existing flue gas cleaning system (legend explained in table 6.4)

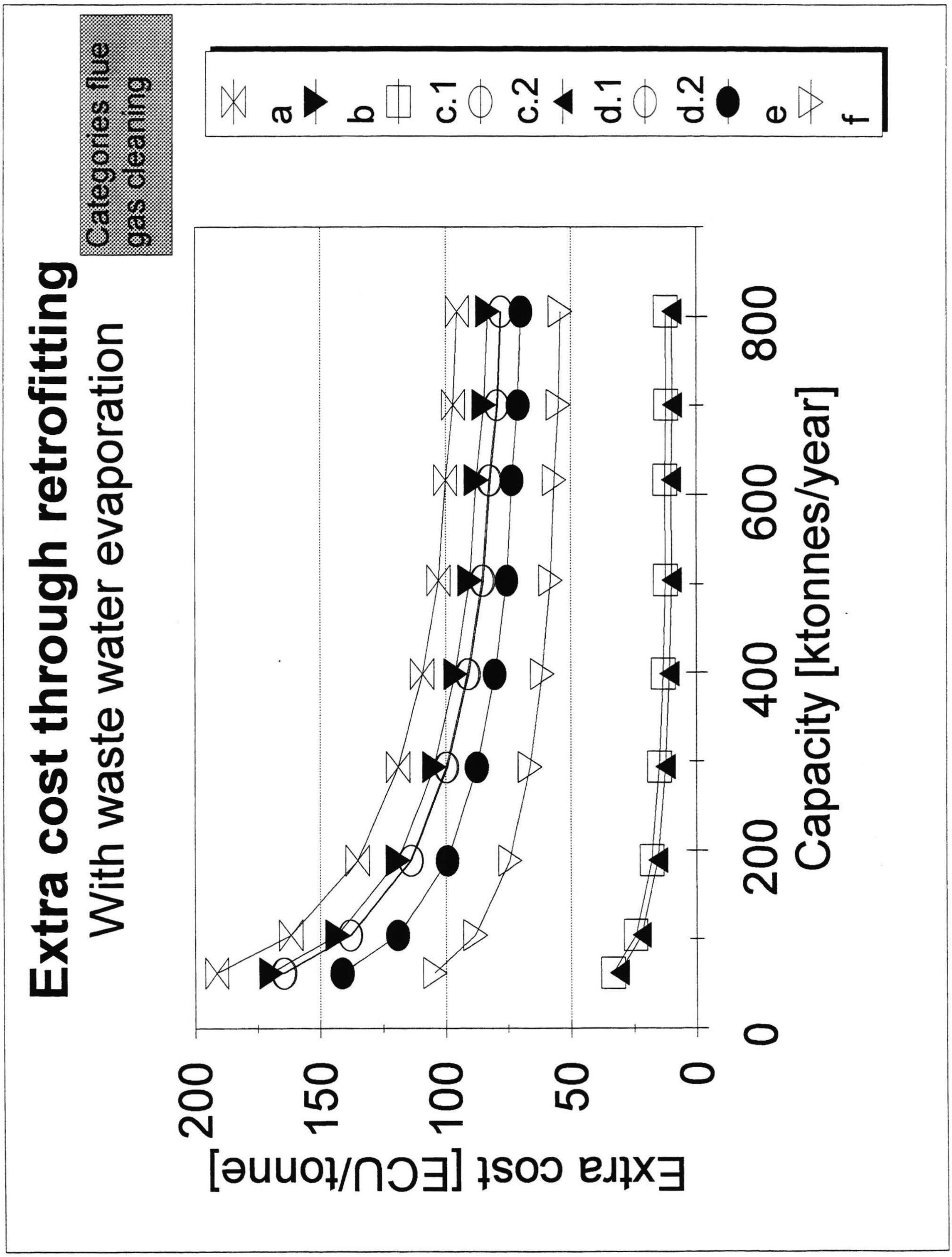


Figure 16 Extra cost per tonne MSW for retrofitting existing installations without waste water evaporation, depending on the already existing flue gas cleaning system (legend explained in table 6.4)

Appendix A

- Abbreviations used in tables
- Data per country

Abbreviations used in tables

Abbreviations used in the table

GASCLEAN
Flue gas cleaning

{blank}	unknown
cy	cyclone
ep	electrostatic precipitator
epw	wet electrostatic precipitator
ff	fabric filter
w	wet scrubber
d	dry scrubber
s	semi-dry scrubber
n	DeNOx-installation 1 SCR 2 SNCR 3 cokesfilter 4 oversized SCR
c	coal-filter
ci	coal injection
NONE	no flue gas cleaning

ENERGSYS
Energy system

N	no energy recovery
Y	energy recovery: type unknown
el	electricity
dh	district heating
sd/ss	sludge drying
cd	compost drying
st	steam generation: purpose unknown
hw	hot water generation: purpose unknown
chp	combined heat and power

Start-up year
CHANGES

E	Extension
M	Modernisation
N	New building
C	Closed

also the year in which it happened/will happen is mentioned

Data per country

A Austria

Population:	7.6	million people
Total MSW:	2,800	ktonnes/year
Per capita:	370	kg/year

Table A.1 Total amount and composition of Municipal Solid Waste generated in Austria per year (1990)

Component	Amount	
	ktonnes/yr	% of total MSW
Putrescibles/Fines	840	30
Paper & cardboard	840	30
Plastic	250	9
Glass	280	10
Metals	110	4
Textiles	80	3
Miscellaneous	390	14
Total	2,800	100

Table A.2 Municipal Solid Waste treatment per category in Austria (1990)

Component	Municipal Solid Waste	
	ktonnes/yr	%
Recycling	170	6
Composting	500	18
Landfill	1,830	65
Combustion	300	11
Total	2,800	100

Existing MSW combustion facilities:
- capacity > 15 tonnes/hour 2

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
A	Wien I (Flötzersteig)	1963		3*6	18.00	el, dh	ep,w2,n4
A	Wien II (Spittelau)	1971		2*15	30.00	el, dh	ep,w2,n4

New MSW combustion facilities:
- Wels: 1995 6.8 tonnes/hour

Sources

- OECD, 1991a+b
- PWMI, 1991
- Hodecek, 1989
- Vogel, 19??
- Gstraunhaler, Ringhofer, 1990
- Sema Group, 1991
- Thomé-Kozmiensky, 1985
- Löffler, 1991
- Lurgi, 19??
- VDI, 1992

B Belgium

Population:	9.9	million people
Total MSW:	3,500	ktonnes/year
Per capita:	352	kg/year

Table B.1 Total amount and composition of Municipal Solid Waste generated in Belgium per year (1990)

Component	**Amount**	
	ktonnes/yr	**% of total MSW**
Putrescibles/Fines	1,650	30
Paper & cardboard	980	30
Plastic	260	9
Glass	245	10
Metals	140	4
Textiles	70	3
Miscellaneous	175	14
Total	3,500	100

Table B.2 Municipal Solid Waste treatment in Belgium (1990)

Component	**Municipal Solid Waste**	
	ktonnes/yr	**%**
Recycling	100	3
Composting	0	0
Landfill	1,500	43
Combustion	1,900	54
Total	3,500	100

Existing MSW combustion facilities:

— 3 < capacity < 15 tonnes/hour	18
— capacity > 15 tonnes/hour	6

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
B	Lokeren	1973	M93	2*1.8	3.60	N	ep
B	Knokke Heist	1975	C94	2*2	4.00	dh	ep
B	Willebroek	1973	C95	2*2.2	4.40	N	ep
B	Melsele (Beveren)	1978	C95	2*2.2	4.40	N	ep
B	Hoevenen	1976	C95?	1*4.5	4.50	N	ep
B	Gent	1979	C95	2*2.5	5.00	N	ep
B	Ronse	1977	C95	2*2.7	5.40	N	ep
B	Houthalen	1984	C95?	2*3	6.00	el	ep
B	Izegem	1976	C94	2*3	6.00	N	cy
B	Heist o/d Berg	1977	C94	2*3.2	6.40	N	ep
B	St. Niklaas	1977	M84/88/89	2*3.6	7.20	el,dh	ep,w2
B	Edegem	1970		2*3.3	6.60	dh	d,ep
B	Roeselare	1976		2*4	8.00	dh	ep,d,ff
B	Menem	1983	C95?	2*4	8.00	N	ep
B	Virginal-Samme (W)	1973		2*5	10.00	N	ep
B	Harelbeke	1977		2*5.5	11,00	el	ep
B	Oostende	1982		2*5.6	11.20	el	ep,w1
B	Eeklo	1981		2*7	14.00	N	ep
B	Thumaide (W)	0		2*5.3,1*5	15.60	Y	ep
B	Wilrijk (Antwerpen)	1980	M93/94	2*10	20.00	N	ep
B	Pont de Loup (Charleroi,W)	1978		2*7.5,1*8	23.00	N	ep
B	Brugge	1981		3*9	27.00	el,dh	ep,w1
B	Herstal (Luik:W)	1990	E93	2*9,2*11	40.00	Y	s,ep
B	Brussels	1985		3*23	69.00	st	ep

New MSW combustion facilities:

- by 2010 all the existing installations will be shut down and replaced by 5 to 7 new large combustion facilities.

Sources

- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- Jaubin, Wijs, 1991
- OVAM, 1989
- Lurgi, 19??
- Schleger, 1991
- Brussel, 19??
- OVAM, 19??
- Vandermeerschen, 1987

CH Switzerland

Population:	6.7	million people
Total MSW:	3,700	ktonnes/year
Per capita:	550	kg/year

Table CH.1 Total amount and composition of Municipal Solid Waste generated in Switzerland per year (1990)

Component	Amount	
	ktonnes/yr	% of total MSW
Putrescibles/Fines	1,110	30
Paper & cardboard	1,150	31
Plastic	480	13
Glass	260	7
Metals	220	6
Textiles	110	3
Miscellaneous	370	10
Total	3,700	100

Table CH.2 Municipal Solid Waste treatment per category in Switzerland (1990)

Component	Municipal Solid Waste	
	ktonnes/yr	%
Recycling	800	22
Composting	250	7
Landfill	450	12
Combustion	2,200	59
Total	3,700	100

Existing MSW combustion facilities:

— capacity < 15 tonnes/hour	22
— capacity > 15 tonnes/hour	8

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
CH	Zermatt	1964		1.3	1.30	Y	ep
CH	Locarno	1969	C95	2*1.6	3.20	N	ep
CH	Brig-Glis/Gamsen	1971	M91	3.5, N.A.	3.50	N	ep,w2
CH	Dietikon (Limattal)	1971	E95	2*1.6,1*0.6	3.80	hw	ep
CH	Lausanne	1958		2*2.8	5.60	el	ep,w2
CH	La Chaux de Fonds	1972		2*3	6.00	Y	ep,w2
CH	St. Gallen	1972	E87; M87	3.3, 3.5	6.80	Y	sda,ep,w2
CH	Oftringen	1974		3.3, 3.6	6.90	hw	ep,w2
CH	Sion	1971	E77	1*3,1*4	7.00	N	ep
CH	Kirchberg/Bazenheid	1976	E84	3*3.5	7.00	Y	sda,ep,w2
CH	Colombier (Cottendart)	1971		2*3.6	7.20	el	ep,w2
CH	Müllheim	1974	C95	4, 3.6	7.60	N	ep
CH	Hefenhofen	1974	C95	2*4.2	8.40	N	ep
CH	Brügg-Biel	1968	E76	5.0, 3.5	8.50	Y	ep,w2
CH	Trimmis	1975		2*4.4	8.80	N	ep,w2
CH	Horgen	1967	E84	7.4, 3.8	11.20	hw	ep,w1
CH	Hinwil	1971	E76	4.3, 7.4	11.70	el	ep,w2
CH	Winterthür	1965	E77;M95	12.5	12.50	Y	ep
CH	Turgi	1970	E83	2*3.6, 5.8	13.00	hw	ep, w2
CH	Niederurnen	1973		4.0, 9.0	13.00	Y	s,ep
CH	Buchs SG	1975	E82	5.0,8.3,N.A.	13.30	el	ep,w2
CH	Monthey	1976		2*7	14.00	el	ep,w2
CH	Zürich/Jozefstrasse	1978		1*15.2	15.20	Y	s,ep,n1
CH	Buchs AG	1974	E84	3*2.9,1*8.3	17.00	hw	ep,w2
CH	Bern	1954	E76;M85	2*9.8	19.60	hw,el	ep
CH	Zuchwil (Emmenspitz)	1976	M87;M92	2*10.0	20.00	el,hw	ep,w2,n2
CH	Zürich/Hagenholz	1969	M82	1*15.2,1*13.	28.20	el	ep,w2
CH	Aire-la Ville (Geneve)	1966		2*6,1*20	32.00	Y	ep,w2
CH	Basel	1944	E66,69	2*8.3,2*12.5	41.60	Y	ep,w2,n2
CH	Luzern	1971	E83	2*16,19	51.00	el	ep,w2

New MSW combustion facilities:
- Geneva 1993 unknown capacity
- Most plants will have scrubbers at the end of 1993

Sources

- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- Thomé-Kozmiensky, 1985
- Bouscaren, Hollier, 1986
- Lurgi, 19??
- EVT, 19??
- VDI, 1992
- Nutec, 1992
- Schweiz, 1990a+b
- Simos, Maystre, 1988
- Larcher, 1990

D Germany

Population: 61.1 million people
Total MSW: 25,000 ktonnes/year

Per capita: 410 kg/year

Table D.1 Total amount and composition of Municipal Solid Waste generated in Germany per year (1990)

Component	Amount	
	ktonnes/yr	% of total MSW
Putrescibles/Fines	11,000	44
Paper & cardboard	6,000	24
Plastic	1,750	7
Glass	2,250	9
Metals	1,500	6
Textiles	500	2
Miscellaneous	2,000	8
Total	25,000	100

Table D.2 Municipal Solid Waste treatment per category in Germany (1990)

Component	Municipal Solid Waste	
	ktonnes/yr	%
Recycling	4000	16
Composting	500	2
Landfill	11,500	46
Combustion	9000	36
Total	25,000	100

Existing MSW combustion facilities:

— capacity < 15 tonnes/hour	12
— capacity > 15 tonnes/hour	37

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
D	Neufahrn/Freising	1970	M78;M87;M89	1*3	3.00	st/dh	d, ff
D	Markt-Oberdorf	1974	M86/87	1*3	3.00	st/dh	d,w2,ff
D	Zirndorf (Furth)	1977	M84;M86/87;M91	1*4.6	4.60	st/dh	ep,w1,ci,ff
D	Heidelberg	1974	M89/90	1*5,7	5.70	cd	ep,ff,w2
D	Kempten (Allgau)	1984	M87	1*7	7.00	st/dh	cy,s,ff
D	Neustadt/Holstein	1984	M96	1*8	8.00	st/chp	cy,w2
D	Ingolstadt	1983	M91/92	1*10	10.00	st/chp	ep,w2,n1,ci,ff
D	Pinneberg	1974	M78;M83;M85;E87/88	2*5	10.00	st/chp	ep,w1
D	Rosenheim	1964	E70;M86-88	1*10.5	10.50	st/chp	s,ff
D	Landshut	1972	E74;E81;M89	2*3,1*6	12.00	st	ep,w2,ep
D	Ulm Weissenhorn	1991		2*6.5	13.00	st/chp	cy,s,ff,w1
D	Solingen	1969	M86;91N	1*6.5,1*7.6	14.10	st/chp	ep,s,ep
D	Hagen	1966	M88	3*5	15.00	st/dh	s,ep
D	Neunkirchen	1970	E77;M86;M90/91	1*5,1*10	15.00	st/chp	ep,w2
D	Bamberg	1978	E81;M88/89	3*6	18.00	st/chp	ep,w2
D	Geiselbullach	1970	E75;E85/86	3*6	18.00	st/chp	cy,d,ff
D	Kassel	1968	E69;M87	2*10	20.00	st/chp	ep,s,ff
D	Kiel-Sud	1975	E80;M94	2*5,1*10	20.00	st/dh	ep,w1
D	Hamburg (Borsigsstrasse)	1931	M59/63;M66/79;M84	2*10.5	21.00	st/chp	s,ep
D	Coburg	1988		2*11	22.00	st/chp	sda,ff,w2,ep
D	Goppingen	1975	M85-87	2*12	24.00	st/chp	cy,ep,w2
D	Wurzburg	1984	M94	2*12.5	25.00	st/chp	d,ff
D	Hamburg (Stell. Moor)	1973	M78;M89	2*13	26.00	st	ep,w2
D	Bonn	1992		3*10	30.00	st/chp	ep,w2,(ci),ff
D	Hameln	1977	E83;M91-93	3*10	30.00	st, dh	d,ep,c,n1,n2
D	Offenbach	1970	M86;M89	3*10	30.00	st/chp	ep,w2,ep
D	Darmstadt	1967	E78;M87/88;N91	1*8.4,2*11	30.40	st/chp	sda,cy,ep,w2
D	Ludwigshafen	1967	89N	1*8,2*12	32.00	st/chp	ep,w2
D	Iserlohn	1970	E74;M84;E88/89	2*8,1*16	32.00	st/chp	ep,w1
D	Leverkusen	1970	E86	2*10,1*12	32.00	st/chp	s,ep
D	Hamm	1986		4*9.5	38.00	st/chp	s,ff
D	Herten	1982	M89;N90	2*20	40.00	st/chp	cy,ep,w2
D	Stapelfeld	1978	M90	2*21	42.00	st/chp	ep,w2
D	Mannheim	1965	E75/78;M89	2*12,1*20	44.00	st/chp	ep,w2,ep
D	Bremerhaven	1977	E87;M89/90	3*15	45.00	st/chp	ep,w2,n2
D	Bielefeld-Herford	1982	E89;M92	3*16	48.00	st/chp	ep, w1
D	Nurnberg	1968	E80;M85;E88/89;M90-93	3*12,1*19	55.00	st/chp	ep,s,ff + s,ep

D	Krefeld	1976 E82;M94	3*19.1	57.30	st/chp	ep,w2,n1,c
D	Frankfurt/M.	1966 M85-87	4*15	60.00	st/chp	s,ep,ff
D	Stuttgart	1965 E72;M77/78;M93/94	3*20	60.00	st/chp	ep,w2,ep,n1
D	Wuppertal	1976 E86	4*12,1*15	63.00	st	ep,w1 + s,ep
D	Essen/Karnap	1987	3*21	63.00	st/chp	ep,w1
D	Bremen	1969 E76;M89/90	3*15,1*20	65.00	st/chp	ep,s,ci,ff
D	Berlin	1967 E71/72;M87-89	7*9.5	66.50	st	d,ff
D	Munchen-Sud	1969 E71;M91	2*35	70.00	st/dh	cy,s,ff,n1
D	Dusseldorf	1965 E75;E80;M89;M91	6*12.5	75.00	st/chp	s,ep,c,n1
D	Schwandorf	1982 E92	3*18.7,1*28	84.10	st/chp	s,ff
D	Oberhausen	1972 E85;M89	4*22	88.00	st	ep,w1
D	Munchen-Nord	1962 E83;92N	2*20,2*35	110.00	st/chp	cy,s,ep + cy,ep,w2

New MSW combustion facilities:

Bonn 1992	unknown capacity
Burgkirchen 199?,	40 tonnes/hour, wet scrubber
Schweinfurt 199?,	24 tonnes/hour, wet scrubber
Berlin 199?,	8.5 tonnes/hour, wet scrubber
Ulm 199?,	13 tonnes/hour, semi-dry and wet scrubber
Plans for plants in Augsburg, Esslingen, Pirmasens, Velsen, Böblingen and Rems-Mürr	

Sources
- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- ISWA, 1991
- Barniske, 1989
- Wijdeven, 1991
- Volund, 19??
- VDI, 1992
- Hösel et al, 1991
- Bauer, Herrler, 1989

DK Denmark

Population:	5.1	million people
Total MSW:	2,600	ktonnes/year
Per capita:	510	kg/year

Table DK.1 Total amount and composition of Municipal Solid Waste generated in Denmark per year (1990)

Component	**Amount**	
	ktonnes/yr	**% of total MSW**
Putrescibles/Fines	1,040	40
Paper & cardboard	910	35
Plastic	130	5
Glass	100	4
Metals	130	5
Textiles	80	3
Miscellaneous		
combustibles	130	5
non-combustibles	80	3
Total	2,600	100

Table DK.2 Municipal Solid Waste treatment per category in Denmark

Component	**Municipal Solid Waste**	
	ktonnes/yr	**%**
Recycling	500	19
Composting	100	4
Landfill	750	29
Combustion	1,250	48
Total	2,600	100

Existing MSW combustion facilities:

— capacity < 15 tonnes/hour	24
— capacity ≥ 15 tonnes/hour	6

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
DK	Videbæk	1981		1*2	2.00	dh	ep
DK	Hammel	1986		1*2.3	2.30	dh	ep,w1
DK	Grenå	1981	M87	1*2.5	2.50	dh	ep
DK	Bornholm (Ronne)	1990		1*2.5	2.50	dh	d,ff
DK	Skagen	1979		1*2.5	2.50	dh	ep
DK	Hadsund	1984		2*1.25	2.50	dh	ep,w1
DK	Hobro	1981	M86	1*3	3.00	dh	ep,w1
DK	Vejen	1989		1*3	3.00	el,dh	d,ep
DK	Ärs	1986		1*3.5	3.50	dh	ep
DK	Middelfart	1972		2*2	4.00	dh	d,ff
DK	Frederikshavn	1965	E72:N93	1*5	5.00	el,dh	ff,w1
DK	Hjorring	1986		2*3	6.00	dh	ep
DK	Taastrup	1967	E89	2*3	6.00	dh	d,ff
DK	Thisted	1978	M86	1*6.3	6.30	el,dh	ep,w2
DK	Nykobing F.	1983	M87	2*3.5	7.00	dh	d,ep
DK	Svendborg	1978	E85	1*3.5,1*4	7.50	dh	ep
DK	Kolding II	1982		2*4	8.00	dh	ep,w1
DK	Nordforbrænding	1969	M87/88;E89	3*3	9.00	dh	d,ff
DK	Næstved	1983	M87	2*4.5	9.00	dh	ep,w1
DK	Skanderborg	1983		1*4,1*5	9.00	el,dh	d,ep + ep,w1
DK	Haderslev	1966	E74:M93	2*4.5	9.00	el,dh	ff,w1
DK	Horsens	1974	E80;M85	2*5	10.00	dh	s,ff
DK	Sonderborg	1969	E73;E84	1*2,2*4	10.00	dh	ep
DK	Slagelse	1970	E81;M85/86	1*4,1*6	10.00	dh	d,ep
DK	Holstebro	1971	M86/87:M93	2*9	18.00	el,dh	ep,w2
DK	Roskilde	1966	E81;E88	2*3.5,2*7	21.00	dh	s,ep + s,ff
DK	Aarhus	1978	M85	2*7.6,1*9.3	24.50	dh	s,ep
DK	Aalborg	1980	E91	2*8,1*12	28.00	el,dh	s,ep + s,ff
DK	Amagerforbrænding	1971	E91	4*12	48.00	el,dh	s,ff
DK	Vestforbrænding	1971	E77	3*12,1*14	50.00	dh	ep,w2

New MSW combustion facilities:
- No new combustion facilities planned

Sources
- Miljostyrelsen, 1989
- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- ISWA, 1991
- DK-Teknik, 1991
- Miljostyrelsen, 1991a+b
- Warmer, 1992
- Tattersley, 1990
- Macdonald, 1991
- Elmlund, 1988

E Spain

Population: 38.9 million people
Total MSW: 13,300 ktonnes/year

Per capita: 340 kg/year

Table E.1 Total amount and composition of Municipal Solid Waste generated in Spain per year (1990)

Component	Amount	
	ktonnes/yr	% of total MSW
Putrescibles/Fines	6,520	49
Paper & cardboard	2,660	20
Plastic	930	7
Glass	1,060	8
Metals	530	4
Textiles	270	2
Miscellaneous:		
combustibles	930	7
non-combustibles	400	3
Total	13,300	100

Table E.2 Municipal Solid Waste treatment per category in Spain (1990) [7, 16, 24, 27, 78]

Component	Municipal Solid Waste	
	ktonnes/yr	%
Recycling	1,700	13
Composting	2,200	17
Landfill	8,650	65
Combustion	750	6
Total	13,300	100

Existing MSW combustion facilities:

— capacity < 15 tonnes/hour	13
— capacity ≥ 15 tonnes/hour	2

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
E	Baztan	0		0.5	0.50	N	NONE
E	Labayen	0		0.5	0.50	N	NONE
E	Valdeprado del Rio	0		1	1.00	N	NONE
E	Cabezon de Liebana	0		1	1.00	N	NONE
E	Ramalas	0		1	1.00	N	NONE
E	Selaya	0		1	1.00	N	NONE
E	Trujillo	0		1	1.00	N	NONE
E	Gerona	1984		2.5	2.50	N	ep
E	Ubrique (Cadiz)	0		2*1.5	3.00	N	
E	Moncada y Reisachs (Barcelona)	1975		2*2.5	5.00	el	ep
E	Mondragon (Guipuzcoa)	1982		2*3.5	7.00	N	cy
E	Son Reus (Palma de Mallorca)	1979		1*8	8.00	el	ep
E	Vigo (Pontevedra)	1972		2*5	10.00	N	cy
E	Tarragona	1991		2*9.6	19.20	el	ep
E	San. Adria De Besos (Barcelona	1975		3*15	45.00	el	ep

New MSW combustion facilities:

- 6 new installations will be built with total capacity of 1640 ktonnes/year (approx. 220-240 tonnes/hour), 199?
- 5 locations are examined for feasibility

Sources

- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- ISWA, 1991
- Spain, 1992
- Cadman, 1989

F France

Population: 56.2 million people
Total MSW: 20,000 ktonnes/year

Per capita: 360 kg/year

Table F.1 Total amount and composition of Municipal Solid Waste generated in France per year (1990)

Component	**Amount**	
	ktonnes/yr	**% of total MSW**
Putrescibles/Fines	5,000	25
Paper & cardboard	6,000	30
Plastic	1200	6
Glass	2400	12
Metals	1000	5
Textiles	600	3
Miscellaneous	3,800	19
Total	20,000	100

Table F.2 Municipal Solid Waste treatment per category in France (1990)

Component	**Municipal Solid Waste**	
	ktonnes/yr	**%**
Recycling	600	3
Composting	2,000	10
Landfill	9,000	45
Combustion	8,400	42
Total	20,000	100

Existing MSW combustion facilities:

– capacity < 15 tonnes/hour	196
– capacity ≥ 15 tonnes/hour	29

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
F	Pauilhac	1979		1*?	0.00	N	
F	Montguyon (Clerac)	1979		1*1	1.00	N	
F	Lezignan	1979		1*1	1.00	N	
F	Lerrain	1979		1*1	1.00	N	
F	Preporche	1982		1*1	1.00	N	
F	Aurillac	1989	*	1*1	1.00	st	d,ff
F	Xertigny	1979		1*1	1.00	N	
F	Contrexeville	1981		1*1	1.00	N	
F	Chauny	1972	E76;*	2*1	1.00	Y	
F	Cesson	1979		1*1	1.00	N	
F	Guise	1987		1*1	1.00	N	
F	Figeac	1981		1*1	1.00	N	
F	Dol de Bretagne	1980		1*1	1.00	N	
F	Saint-Viaud	1988		1*1	1.00	N	
F	Villedieu	1982		1*1	1.00	N	
F	St Alban d'Ay	1987		1*1	1.00	N	
F	Saint Austreberthe	1974		1*1	1.00	N	
F	St Laurent du Pont	1981		1*1.2	1.20	N	
F	Juigne (Pont de ce)	1978		1*1.2	1.20	N	
F	Faverges	1976		1*1.2	1.20	N	
F	La Charite sur Loire	1976		1*1.5	1.50	N	
F	Is-Sur-Tille	1983		1*1.5	1.50	Y	
F	Villefranche	1976		1*1.5	1.50	N	
F	Cazeres	1975		1*1.5	1.50	N	
F	Villefranche	1974		1*1.5	1.50	N	
F	Tonneins	1979		1*1.5	1.50	N	
F	Valdahon	1982		1*1.5	1.50	N	
F	Nogent les Montbard	1981		1*1.5	1.50	N	
F	Saintes Marie	1972		1*1.5	1.50	N	
F	Ouarvill (Auneau)	1976		1*1.5	1.50	N	
F	Rouy (St Saulge)	1982		1*1.5	1.50	N	
F	Pont de Beauvoisin	1983		1*1.5	1.50	Y	
F	Millas	1981		1*1.5	1.50	Y	
F	Lavilledieu	1980		1*1.5	1.50	N	
F	La Ferte Bernard	1980		1*1.5	1.50	N	
F	Le Cheylard	1984		1*1.5	1.50	N	
F	Mer	1987	*	1*1.5	1.50	Y	

F	Saulieu	1984		1*1.5	1.50	N	
F	Arudy	1982		1*1.5	1.50	N	
F	Bouzon	1977		1*1.5	1.50	N	
F	Crolles	1976		1*1.8	1.80	Y	
F	Chateaurenard	1976		1*1.8	1.80	N	
F	Segre (Ste Gemmes)	1974		1*1.8	1.80	N	
F	Bourg d'Oisans	1978		1*1.8	1.80	N	
F	Privas	1976		1*1.8	1.80	N	
F	Fos sur Mer	1973		1*2	2.00	N	
F	Lacq	1990	*	1*2	2.00	Y	d,ff
F	Lasse (Noyant)	1981		1*2	2.00	N	
F	Tarare	1981		1*2	2.00	Y	
F	Sousville	1987		2*1	2.00	Y	
F	L'Aigle	1973		1*2	2.00	N	
F	Chateau Gontier	1981		1*2	2.00	Y	
F	Quillan	1971		1*2	2.00	N	
F	Pont Audemer	1972		1*2	2.00	N	
F	Bessines	1985	E87	2*1	2.00	N	
F	Feche l'Eglise	1970		2*1	2.00	N	
F	Auvillar	1983		2*1	2.00	N	
F	Bonneval	1973		1*2	2.00	N	
F	Issoudun	1979	E83	2*2	2.00	N	
F	Isola 2000	1976		1*2	2.00	N	
F	Courtenay	1979	E82	2*1	2.00	N	
F	Briancon	1974		1*2	2.00	N	
F	St Hilaire	1981		2*1	2.00	N	
F	St Girons	1977		1*2	2.00	N	
F	Loriol-Du-Comtat	1973		2*1	2.00	N	
F	Surgeres	1976		1*2	2.00	Y	
F	St Pol de Leon	1974		1*2	2.00	N	
F	St Pierre sur Dives	1980		2*1	2.00	N	
F	Grans	1973		1*2	2.00	N	
F	Gien	1975		2*1	2.00	N	
F	Garrigues	1985		1*2	2.00	N	
F	Chatillon	1985		1*2.1	2.10	Y	
F	St Quentin	1968		1*2.2	2.20	Y	
F	St Chamond	1968		1*2.3	2.30	N	cy
F	Cosne sur Loire	1975		1*2.4	2.40	N	

F	Flers	1973	1*2.5	2.50	N	
F	Moriville	1974	1*2.5	2.50	N	
F	Bayonne	1990 *	1*2.5	2.50	Y	s, ff
F	Canet en Roussillon	1971	1*2.5	2.50	N	
F	Apt	1984	1*2.5	2.50	Y	
F	St Marcellin	1979	1*2.5	2.50	N	
F	Bourg de Thizy	1977	1*2.5	2.50	N	
F	Rumilly	1976	1*2.5	2.50	N	
F	Nouan le Fuzelier	1983	1*2.7	2.70	N	
F	Orange	1977	1*2.8	2.80	N	cy
F	Chinon	1984	1*2.8	2.80	st	ep
F	Le Treport	1972	1*3	3.00	N	cy
F	Vesoul	1968	2*1.5	3.00	N	
F	Agde	1970	1*3	3.00	N	
F	Lisieux	1973	1*3	3.00	N	
F	Argeles	1975	1*3	3.00	N	
F	Arles	1977	1*3	3.00	N	
F	Redon	1975	1*3	3.00	N	
F	St Georges sur l'Aa	1972	1*3	3.00	N	
F	St Foy l'Argentiere	1985	2*1.5	3.00	Y	
F	Sens	1989	2*1.5	3.00	Y	d,ff
F	Tignes	1985	2*1.5	3.00	N	
F	Pezenas	1981	1*3	3.00	N	
F	Nevers	1965	1*3	3.00	N	
F	Messanges	1976	1*3	3.00	N	
F	Tinteniac	1984	2*1.5	3.00	N	
F	Pontmain	1984	1*3	3.00	st	ep
F	Pontcharra	1977	1*3	3.00	N	cy
F	Douarnenez	1974	1*3	3.00	N	
F	Coulommiers	1981	1*3	3.00	N	
F	Fontainebleau	1966	1*3	3.00	N	
F	Fecamp	1975	1*3	3.00	N	
F	Jonzac	1982	1*3	3.00	Y	
F	Nogent le Rotrou	1976	1*3.2	3.20	N	
F	Evans (Dole)	1974	1*3.2	3.20	N	
F	Pithiviers	1985	1*3.25	3.25	st	cy
F	Chateaudun	1976	1*3.4	3.40	N	
F	St Jean D'Angely	1981 *	1*3.5	3.50	Y	

F	Ales	1975		1*3.5	3.50	N	
F	Lillebonne	1975		2*1.8	3.60	st	cy
F	Arrabloy (Gien)	1975		2*1.8	3.60	N	
F	Albertville	1985		1*3.9	3.90	N	ep
F	Perpignan	1974		1*4	4.00	N	ep
F	Pontivy	1990	*	1*4	4.00	Y	d,ff
F	Cavalaire	1978		2*2	4.00	N	
F	Vitre	1988		1*4	4.00	st	d,ff
F	Pavilly	1974		1*4	4.00	N	
F	Agen	1983		1*4	4.00	Y	
F	Carpentras	1973		2*2	4.00	N	cy
F	Cholet	1983		1*4	4.00	Y	
F	Vaux Le Penil	1976		1*4	4.00	N	
F	Chantelle	1982		1*4	4.00	Y	
F	Seguinere	1983	*	1*4	4.00	Y	
F	Dinan	1976		2*2	4.00	N	
F	Cluses	1982		1*4	4.00	N	w1
F	Sillans la Cascade	1972	E75	2*2	4.00	Y	
F	Bernay	1974		2*2	4.00	N	
F	Medis	1987		2*2	4.00	N	
F	St Omer	1975		1*4.2	4.20	N	
F	Plouharnel	1970		1*4.2	4.20	N	cy
F	Montereau	1973		1*4.2	4.20	N	ep
F	Ozoir la Ferriere	1976		1*4.5	4.50	N	ep
F	Villefranche	1984		1*4.5	4.50	st,dh	
F	Pontarlier	1988			4.50	Y	w1
F	Arras	1976		1*4.5	4.50	st	ep
F	Strazeele	1973		2*1.8,1*1	4.60	N	cy
F	Oyonnax (Groissiat)	1974		2*2.5	5.00	N	
F	Rochefort	1990		2*2.5	5.00	st	ep,w1
F	Dieppe	1971		2*2.5	5.00	st	cy
F	Deauville	1974	*	2*2.5	5.00	Y	
F	Montauban	1986		1*5	5.00	Y	d,ff
F	Thonon	1988		1*5	5.00	st	s,ep
F	St Pierre Oleron	1976	E79	2*2.5	5.00	N	
F	Isere	1986	*	1*5	5.00	Y	
F	Vedenes	1971		1*5	5.00	N	
F	Tronville	1983		1*5	5.00	Y	

F	Chateauroux	1972		2*3	6.00	N	
F	Thonon	1972	E76	1*2,1*4	6.00	N	
F	Lescar	1975		2*3	6.00	N	
F	Forbach	1976		2*3	6.00	N	
F	Niort	1972		2*3	6.00	N	
F	Couronne	1973	E86	1*5,1*1	6.00	N	
F	Blois	1971		2*3.1	6.20	Y	
F	Colombelles	1972	*	1*7	7.00	Y	
F	Benesse	1972	E85	1*3,1*4	7.00	N	
F	Besancon	1971			7.00	Y	ep
F	Guingamp	1972		1*3.5	7.00	N	
F	La Teste (Arcachon)	1974		2*3.6	7.20	N	
F	Belfort	1988	E90	2*4	8.00	st	ep
F	Lagny	1985		1*8	8.00	st	ep
F	Poitiers	1984		2*4	8.00	Y	
F	Chavanod	1986	*	2*4	8.00	Y	
F	Ensues la Redonne	1972		2*4	8.00	N	
F	Concarneau	1989		2*4	8.00	Y	d,ep
F	Epinal	1983		2*4	8.00	Y	
F	Chartres	1971		2*4	8.00	N	
F	La Rochelle	1988		2*4	8.00	st	d
F	Creil	1970		2*4	8.00	N	
F	Annecy	1986		2*4.2	8.40	Y	
F	Dunkerque	1971		2*4.4	8.80	N	
F	Montbeliard	1989		2*4.5	9.00	st	s,ff
F	Mulhouse	1972		2*4.5	9.00	st	ep
F	Limoges	1989		2*5	10.00	hw	s,ep
F	Bayet	1982	*	2*5	10.00	Y	
F	La Beuvriere	1978	*	2*5	10.00	st	ep
F	Chambery	1977		2*5	10.00	N	
F	Denain	1977		2*5	10.00	N	
F	Halluin (Lille)	1967		2*5	10.00	N	
F	Bruay en Artois	1979		2*5	10.00	Y	
F	Rennes	1968		2*5	10.00	st	
F	Brive	1973	E83	3*3.5	10.50	st	cy
F	Henin Beaumont	1973	E78	3*3.5	10.50	N	ep
F	Hagueneau	1990	*	2*5.5	11.00	st	s
F	Maubeuge	1980		2*5.5	11.00	st	ep

F	Massy	1986	E88	2*5.5	11.00	st	ep,w1
F	Colmar	1988		2*6	12.00	st	s
F	Le Mans	1975	M91;*	1*12	12.00	st	w1
F	Metz	1970		2*6	12.00	st	ep
F	Reims	1989		2*6.5	13.00	hw	s,ff
F	Noyelle	1973		2*6.7	13.40	N	
F	Villejust	1984		1*6,1*8	14.00	hw	s,ep
F	Caen	1972	E86	2*7.5	15.00	Y	
F	Valenciennes	1977	E87	3*5	15.00	Y	
F	Argenteuil	1975		2*7.5	15.00	st	ep
F	Angers	1974		3*5	15.00	st	ep
F	Nancy	1974		2*8	16.00	Y	
F	Bordeaux	1984		2*8	16.00	st	w1
F	Creteil	1979		2*8	16.00	st	ep
F	Rungis	1981	E85	2*8.5	17.00	hw	ep
F	Brest	1989		2*9	18.00	st	s
F	Antibes (Cannes)	1970		2*9	18.00	N	
F	Grenoble	1972	E77	3*6.25	18.75	st	ep
F	Nantes	1987		2*9.5	19.00	hw	s,ep
F	Rouen	1970		2*10	20.00	st	d,ff
F	Sarcelles	1978	E80	2*10	20.00	Y	s,ep
F	Carriere	1977	E87	2*10	20.00	st	s,ep
F	Thiverval Grignon	1974		2*10	20.00	hw	ep
F	Lyon Nord	1989		2*12	24.00	st	w1
F	Le Havre	1970	E75	3*8	24.00	st	ep
F	Toulouse	1969	E75	3*8	24.00	st	ep
F	Toulon	1985		2*12	24.00	st	s,ep
F	Dijon	1975		2*12.5	25.00	st	ep
F	Wasquehal	1975	E81	3*10	30.00	N	ep
F	Sequedin	1973	E81	3*10	30.00	N	ep
F	Nice	1977	E81	3*12	36.00	st	s,ep
F	Lyon Sud	1963	M89	3*12	36.00	st	w1
F	Strasbourg	1974		4*11	44.00	st	ep
F	Issy-Les-Moulineaux	1965		4*15	60.00	st	ep,w1
F	St Ouen	1990		3*28	84.00	el, dh	ep,w1
F	Ivry-Sur-Seine	1969		2*50	100.00	st	ep

New MSW combustion facilities:
- no information available

Sources
- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- ISWA, 1991
- France, 1990
- Bouscaren, Houllier, 1986
- EVT, 19??
- Schleger, 1991
- Souet, 1990

GR Greece

Population:	10.0	million people
Total MSW:	3,150	ktonnes/year
Per capita:	310	kg/year

Table GR.1 Total amount and composition of Municipal Solid Waste generated in Greece per year (1990)

Component	Amount	
	ktonnes/yr	% of total MSW
Putrescibles/Fines	1,670	53
Paper & cardboard	570	18
Plastic	220	7
Glass	100	3
Metals	130	4
Miscellaneous (textiles incl.)	470	15
Total	3,150	100

No information is available to us on the composite
No information on treatment schemes in Greece.
No MSW combustion facilities at present.
No MSW combustion facilities planned.

Sources
- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- ISWA, 1991
- Papachristou, 1988
- Greece, 1991
- Moussiopoulos, 1992

I Italy

Population:	57.5	million people
Total MSW:	17,500	ktonnes/year
Per capita:	300	kg/year

Table I.1 Total amount and composition of Municipal Solid Waste generated in Italy per year (1990)

Component	Amount	
	ktonnes/yr	% of total MSW
Putrescibles/Fines	7,000	40
Paper & cardboard	3,850	22
Plastic	1,230	7
Glass	1,400	8
Metals	520	3
Miscellaneous textiles incl.)	3,500	20
Total	17,500	100

Table I.2 Municipal Solid Waste treatment per category in Italy (1990)

Component	Municipal Solid Waste	
	ktonnes/yr	%
Recycling	500	3
Composting	1,200	7
Landfill	13,000	74
Combustion	2,800	16
Total	17,500	100

Existing MSW combustion facilities:

— capacity < 15 tonnes/hour	23
— capacity > 15 tonnes/hour	5

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
I	Castelnuovo di Garfagnana (Lu)	1977			1.50	N	
I	Moraro	1981			1.88	N	
I	Abbiategrasso	1970			2.50	N	
I	Salsomaggiore	1972			3.00	N	
I	Vercelli	1977	E92		3.10	Y	
I	Pollenza	1988			3.33	Y	
I	Schio	1983	M91		3.70	Y	
I	Ferrara	1975	E	1*4.2	4.20	N	ep
I	Sassari	1967			5.00	N	
I	Montale (Agliana)	1978			5.00	Y	
I	Padova	1967	M72	1*5.8	5.80	hw	d,ep
I	Bergamo	1965		2*3.1	6.20	st	ep
I	Messina I	1976			8.33	N	
I	Livorno	1973		2*4.2	8.40	Y	ep
I	Reggio Emilia	1967		2*4.2	8.40	st	d
I	Milano I (Zama)	1969		2*5	10.00	st	w1
I	Desio	1976		2*5	10.00	st	w1
I	Valmadrera (Lecco)	1981			10.00	Y	
I	Como	1967			11.25	Y	
I	Busto Arsizio	1972		2*5.7	11.40	N	ep
I	Modena	1980		2*6	12.00	st	ep
I	Parma	1975		2*6.25	12.50	N	ep
I	Coriano (Riccione)	1976			12.50	Y	
I	Trieste	1972		3*5	15.00	N	ep
I	Bolzano (Alto Adige)	1976	E84,E92		20.80	Y	
I	Bologna	1970		3*8.3	24.90	st, el	ep
I	Milano II (Figino)	1975		2*12.5	25.00	st	w1
I	Granarolo	1974			25.00	Y	

New MSW combustion facilities:
- no information available

Sources
- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- ISWA, 1991
- Italy, 1990
- Fraja Frangipane, 19??
- Sim, 1988

IRL Ireland

Population:	3.5	million people
Total MSW:	1,100	ktonnes/year
Per capita:	310	kg/year

Table IRL.1 Total amount and composition of Municipal Solid Waste generated in Ireland per year (1990)

Component	Amount	
	ktonnes/yr	% of total MSW
Putrescibles/Fines	610	55
Paper & cardboard	220	20
Plastic	110	10
Glass	30	3
Metals	30	3
Textiles	30	3
Miscellaneous	70	6
Total	1,100	100

Table IRL.2 Municipal Solid Waste treatment per category in Ireland (1990)

Component	Municipal Solid Waste	
	ktonnes/yr	%
Recycling	35	3
Composting	0	0
Landfill	1,065	97
Combustion	0	0
Total	1,100	100

No MSW combustion facilities at present.
No MSW combustion facilities planned.

Sources

- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- Schoenberg, 1991
- Ireland, 1992

L Luxembourg

Population:	0.4	million people
Total MSW:	180	ktonnes/year
Per capita:	480	kg/year

Table L.1 Total amount and composition of Municipal Solid Waste generated in Luxembourg per year (1990)

Component	**Amount**	
	ktonnes/yr	**% of total MSW**
Putrescibles/Fines	85	47
Paper & cardboard	50	28
Plastic	13	7
Glass	13	7
Metals	7	4
Textiles	4	2
Miscellaneous	9	5
Total	180	100

Table L.2 Municipal Solid Waste treatment per category in Luxembourg (1990)

Component	**Municipal Solid Waste**	
	ktonnes/yr	**%**
Recycling	4	2
Composting	2	1
Landfill	39	22
Combustion	135	75
Total	180	100

Existing MSW combustion facilities:

— capacity > 15 tonnes/hour	1

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
L	Leudelange	1976	E85,M88	3*8	24	st	ep,s,ff

New MSW combustion facilities:
- no changes in existing situation foreseen

Sources
- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- Eickmann, 1992
- EVT, 19??
- Kirsch, 19??

N Norway

Population:	4.2	million people
Total MSW:	2,000	ktonnes/year
Per capita:	470	kg/year

Table N.1 Total amount and composition of Municipal Solid Waste generated in Norway per year (1990)

Component	**Amount**	
	ktonnes/yr	**% of total MSW**
Putrescibles/Fines	500	25
Paper & cardboard	640	32
Plastic	140	7
Glass	80	4
Metals	80	4
Textiles	40	2
Miscellaneous:		
combustibles	280	14
non-combustibles	240	12
Total	2,000	100

Table N.2 Municipal Solid Waste treatment per category in Norway (1990)

Component	**Municipal Solid Waste**	
	ktonnes/yr	**%**
Recycling	140	7
Composting	100	5
Landfill	1,330	67
Combustion	430	22
Total	2,000	100

Existing MSW combustion facilities:

– capacity < 15 tonnes/hour	17
– capacity ≥ 15 tonnes/hour	1

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
N	Haugerud V. sentral (Oslo)			1*0.35	0.35		cy
N	Hjartdal			1*0.4	0.40		cy
N	Tokke			1*0.4	0.40		cy
N	Nordkapp			1*0.4	0.40		cy
N	Drangedal			1*0.5	0.50		cy
N	Lebesby			1*0.5	0.50		cy
N	Vagsoy (Maloy)			1*0.8	0.80		cy
N	Fjaler			1*1.0	1.00		cy
N	Senja (Lenvik)			1*1.1	1.10		cy
N	Ardal			2*0.65	1.30		cy
N	Indre Sunnfjord (Forde)			2*0.75	1.50		cy
N	Bremanger			1*1.5	1.50		cy
N	Hallingdal (Kleivi)			1*3	3.00		cy
N	Alesund	0		1*5	5.00	st, dh	ep, w1
N	Fredrikstad	0		2*4.5	9.00	st, dh	ep, w1
N	Trondheim	1986		2*6	12.00	st, dh	ep, w1
N	Oslo (Haraldrud)	0		2*6.5	13.00	st, dh	ep, w1
N	Oslo (Klemetsrud)	0		2*10	20.00	st, dh	ep, w1

New MSW combustion facilities:
- two permits for combustion facilities have been granted, but no decisions on size, location, etc. have been made yet.

Sources
- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- ISWA, 1991
- Pettersen, Namdal, 1992
- Lurgi, 19??
- Norway, 1990a+b
- Götaverken, 19??

NL The Netherlands

Population:	14.8	million people
Total MSW:	7,700	ktonnes/year
Per capita:	520	kg/year

Table NL.1 Total amount and composition of Municipal Solid Waste generated in The Netherlands per year (1990)

Component	**Amount**	
	ktonnes/yr	**% of total MSW**
Putrescibles/Fines	2,930	38
Paper & cardboard	2,700	35
Plastic	540	7
Glass	540	7
Metals	390	5
Textiles	150	2
Miscellaneous:		
combustibles	310	4
non-combustibles	150	2
Total	7,700	100

Table NL.2 Municipal Solid Waste treatment per category in The Netherlands (1990)

Component	**Municipal Solid Waste**	
	ktonnes/yr	**%**
Recycling	1,200	16
Composting	350	3
Landfill	3,450	45
Combustion	2,700	35
Total	7,700	100

Existing MSW combustion facilities:

— capacity < 15 tonnes/hour	4
— capacity ≥ 15 tonnes/hour	6

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
NL	Eindhoven (Philips)	1986		1*3.5	3.50	el, dh	ep, w1
NL	Roosendaal	1976	C98	2*4	8.00	sd, dh	d,ff,w2 + ep
NL	ARN (Nijmegen)	1986		1*9	9.00	el	ep, w1
NL	Alkmaar	1971	M91, C94	3*4	12.00	N	d, ff
NL	Gevudo (Dordrecht)	1972	M90	4*7	28.00	el, ss	ep, w2
NL	Arnhem (AVIRA)	1975	M93	1*12,2*15	42.00	st, dh	ep, w2
NL	ROTEB Rotterdam	1963	M93	4*12.5	50.00	el	ep,w2,c,n1
NL	Den Haag	1968	E74: C94?	3*12.5,1*15	52.50	el, dh	ep
NL	AVI-Amsterdam	1993		4*28	112.00	st,el	ep,sda,ep,w2,n2
NL	AVR (Rotterdam)	1972	M93	6*22	132.00	st, hw	ep,w2,n1,c

New MSW combustion facilities:

- Alkmaar, 1995, 55.5 tonnes/hour, wet scrubber
- Extension AVR Rotterdam with 27 tonnes/hour, 1993
- Extension for 2 plants: total extra capacity 230 ktonnes/year
- Closing down: 1 in 1993: 1 * 52.5 tonnes/hour, 1 in 1995: 12 tonnes/hour
- 5 new combustors planned before the year 2000: total capacity 2350 ktonnes/year.

Sources

- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- ISWA, 1991
- TNO 1992
- Wijdeven, 1991
- RIVM, 1989
- Brasser, 1990
- The Netherlands, 1989
- Beusekom, 1991
- Nagelhout et al, 1989
- Folmer, 19??

P Portugal

Population:	10.3	million people
Total MSW:	2,650	ktonnes/year
Per capita:	260	kg/year

Table P.1 Total amount and composition of Municipal Solid Waste generated in Portugal per year (1990)

Component	Amount	
	ktonnes/yr	% of total MSW
Putrescibles/Fines	1,590	60
Paper & cardboard	580	22
Plastic	110	4
Glass	80	3
Metals	110	4
Miscellaneous (textiles incl.)	190	7
Total	2,650	100

Table P.2 Municipal Solid Waste treatment per category in Portugal (1990)

Component	Municipal Solid Waste	
	ktonnes/yr	%
Recycling	0	0
Composting	400	15
Landfill	2,250	85
Combustion	0	0
Total	2,650	100

No MSW combustion plants at present.
No information available on new plants planned.

Sources
- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- Warmer, 1989
- Cadman, 1989

S Sweden

Population: 8.5 million people
Total MSW: 3,200 ktonnes/year

Per capita: 380 kg/year

Table S.1 Total amount and composition of Municipal Solid Waste generated in Sweden per year (1990)

Component	**Amount**	
	ktonnes/yr	**% of total MSW**
Putrescibles/Fines	960	30
Paper & cardboard	1,280	40
Plastic	260	9
Glass	220	7
Metals	100	3
Textiles	60	2
Miscellaneous	290	9
Total	3,200	100

Table S.2 Municipal Solid Waste treatment per category in Sweden (1990)

Component	**Municipal Solid Waste**	
	ktonnes/yr	**%**
Recycling	500	16
Composting	100	3
Landfill	1,100	34
Combustion	1,500	47
Total	3,200	100

Existing MSW combustion facilities:

— capacity < 15 tonnes/hour	15
— capacity ≥ 15 tonnes/hour	6

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
S	Landskrona	1982			0.00	dh	d,ff
S	Eksjö	1979	E81		0.00	dh	w1, cy/ff
S	Handen	1967	M91	1*2.5	2.50	dh	ff
S	Mora	1980	M90	1*3.15	3.15	dh	d,ff
S	Kiruna	1985	E91	2*2.2	4.40	dh	ep
S	Karlskoga	1986		1*5	5.00	dh	ep,w1
S	Bollnäs	1983		2*2.6	5.20	dh	cy,ff
S	Borlange	1983		1*5.5	5.50	dh	w1,ep
S	Avesta	1980		2*2.9	5.80	dh	w1,d,ff
S	Västervik	1984		2*3	6.00	dh	ff
S	Karlstad	1986		1*7	7.00	dh	d,ff
S	Sundsvall	1984	M87;M93	1*8	8.00	dh	ep,ff,n2
S	Köping	1971	M91	2*5	10.00	dh	d,ff,ep
S	Halmstad	1971	M84	2*5	10.00	dh	ep,n2
S	Lidköping	1986		2*5.9	11.80	dh	d.ff
S	Umea	1970	E85	2*4,1*7	15.00	dh	d,ff
S	Malmö	1973	M81	2*14	28.00	dh	d,ff,n2
S	Uppsala	1961	E71,82;M89	2*3,1*10,1*15	31.00	dh	w1,d,ff,n2
S	Linköping	1981	E83/84	1*7,2*12	31.00	dh	d,ep
S	Stockholm	1970	E86	2*11,1*15	37.00	el, dh	d,ff
S	Göteborg	1972	E76:M88/89;M92	3*13	39.00	el, dh	ep,w1,n2

New MSW combustion facilities:
- Extension of the Goteborg combustor with 105 ktonnes/year

Sources
- OECD, 1991a+b
- Haley, 1990
- PWMI, 1991
- Hagenmaier, 1989
- Sema Group, 1991
- Thomé-Kozmiensky, 1985
- Svenska, 1991
- ISWA, 1991
- VDI, 1992
- Gotaverken, 19??
- RVF, 1990
- Bergström, 1989

SF Finland

Population:	5.0	million people
Total MSW:	2,500	ktonnes/year
Per capita:	500	kg/year

Table SF.1 Total amount and composition of Municipal Solid Waste generated in Finland per year (1990)

Component	Amount	
	ktonnes/yr	% of total MSW
Putrescibles/Fines	750	30
Paper & cardboard	1,000	40
Plastic	150	6
Glass	100	4
Metals	80	3
Miscellaneous (textiles incl.)	430	17
Total	2,500	100

Table SF.2 Municipal Solid Waste treatment per category in Finland (1990)

Component	Municipal Solid Waste	
	ktonnes/yr	%
Recycling	375	15
Composting	0	0
Landfill	2,075	83
Combustion	50	2
Total	2,500	100

Existing MSW combustion facilities:

– capacity < 15 tonnes/hour	1

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
SF	Turku	1975		2*5	10.00	hw, dh	ep

New MSW combustion facilities:
- Pori, 1993/4, 34-60 ktonnes/year
- Helsinki, 199?, 400-600 ktonnes/year (uncertain)

Sources
- OECD, 1991a+b
- PWMI, 1991
- Sema Group, 1991
- Kuusisto, 1992
- Ojala, 1991
- Finland, 1987
- Finland, 1992

UK United Kingdom

Population: 57.2 million people
Total MSW: 30,000 ktonnes/year

Per capita: 520 kg/year

Table UK.1 Total amount and composition of Municipal Solid Waste generated in the United Kingdom per year (1990)

Component	**Amount**	
	ktonnes/yr	**% of total MSW**
Putrescibles/Fines	12,600	42
Paper & cardboard	8,400	28
Plastic	2,100	7
Glass	2,400	8
Metals	2,700	9
Textiles	1,200	4
Miscellaneous:		
combustibles	300	1
non-combustibles	300	1
Total	30,000	100

Table UK.2 Municipal Solid Waste treatment per category in the United Kingdom (1990)

Component	**Municipal Solid Waste**	
	ktonnes/yr	**%**
Recycling	600	2
Composting	0	0
Landfill	27,000	90
Combustion	2,400	8
Total	30,000	100

Existing MSW combustion facilities:

— capacity < 15 tonnes/hour	16
— capacity ≥ 15 tonnes/hour	15

COUNTRY	LOCATION	STARTUP	CHANGES	UNITSCAP	TOTCAPHR	ENERGSYS	GASCLEAN
UK	Orkney	1960-75	C95	2*1	2.00	N	NONE
UK	Aberdeen	1960-75	C95	2*1	2.00	N	NONE
UK	Worcester	1972	C95	2*2	4.00	N	cy
UK	Belfast	1960		1*4	4.00	N	ep
UK	Shetlands	1960-75	C95	6*1	6.00	N	NONE
UK	Scillies	1974		1*7	7.00	N	cy
UK	Rochdale	1960-75	C95	1*8	8.00	N	ep
UK	Southampton (Marchwood)	1975		1*9	9.00	N	ep
UK	Winchester	1971		1*9	9.00	N	ep
UK	Basingstoke	1969	C95	1*9	9.00	N	ep
UK	Exeter	1960	C95?	1*9.5	9.50	N	ep
UK	Altringham	1960	C95	2*5	10.00	N	ep
UK	Huddersfield	1975		2*6	12.00	N	ep
UK	Havant	1974		1*14	14.00	N	ep
UK	Dudley	1970		2*7	14.00	N	ep
UK	Dundee	1978		2*7	14.00	N	ep
UK	Derby	1969	C95?	2*7.5	15.00	N	cy
UK	Bolton	1974	C95?	1*16	16.00	N	ep
UK	Glasgow (Linwood)	1960-75	C95?	2*8	16.00	N	ep
UK	Jersey (Bellozane)	1979	M92	2*5,1*7.5	17.50	el	ep
UK	Sheffield	1976		2*10	20.00	hw, dh	ep
UK	Wolverhampton	1973		2*10	20.00	N	ep
UK	Sunderland	1960-75		2*10	20.00	N	ep
UK	Tynemouth	1960-75		2*11	22.00	N	ep
UK	Stoke on Trent	1976		2*11	22.00	N	ep
UK	Nottingham	1973		2*11.5	23.00	el, dh	ep
UK	Birmingham (Tyseley)	1977		2*15	30.00	N	ep
UK	Bristol	1960		2*15	30.00	N	ep
UK	Cleveland	1960		2*16	32.00	N	ep
UK	Coventry	1975		3*12	36.00	hw	ep
UK	Edmonton (N-London)	1970		5*14	70.00	el	ep

New MSW combustion facilities:
- London, 400 ktonnes/year, 1994?
- London, 1200-1500 ktonnes/year, 199?
- Leeds, 300 ktonnes/year, 199?
- Isle of Man, 24 ktonnes/year, 199?
- Portsmouth, 300 ktonnes/year, on old site
- Birkenhead, 18 ktonnes/year, 1994
- Approx. 20 of the 31 combustion facilities will close down before 1996
- Plans for combustors in Derby and Birmingham on old sites

Sources
- Patel, 1991
- OECD, 1991a+b
- PWMI, 1991
- Clayton et al, 1991
- Sema Group, 1991
- ISWA, 1991
- Warmer, 1992
- Cooper, 19??

Appendix B Combustion facilities in Europe, per capacity category, per flue gas cleaning category and per country, as total number and capacity per category

Unknown

	<= 3 ton/hr		3 to 15 ton/hr		>= 15 ton/hr		total per country	
	number	total cap.	number	total cap.	number	total cap.	number	ton/hr
A	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0
CH	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0
DK	0	0	0	0	0	0	0	0
E	1	3	0	0	0	0	1	3
F	98	188	51	312	4	64	153	564
I	4	8.9	9	62.2	2	45.8	15	116.9
L	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	0
NL	0	0	0	0	0	0	0	0
S	0	0	0	0	0	0	0	0
SF	0	0	0	0	0	0	0	0
UK	0	0	0	0	0	0	0	0
TOTAL	103	199.9	60	374.2	6	109.8	169	683.9

No flue gas cleaning

	<= 3 ton/hr		3 to 15 ton/hr		>= 15 ton/hr		total per country	
	number	total cap.	number	total cap.	number	total cap.	number	ton/hr
A	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0
CH	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0
DK	0	0	0	0	0	0	0	0
E	7	6	0	0	0	0	7	6
F	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0
L	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	0
NL	0	0	0	0	0	0	0	0
S	0	0	0	0	0	0	0	0
SF	0	0	0	0	0	0	0	0
UK	2	4	1	6	0	0	3	10
TOTAL	9	10	1	6	0	0	10	16

Only dust removal

	<= 3 ton/hr		3 to 15 ton/hr		>= 15 ton/hr		total per country	
	number	total cap.	number	total cap.	number	total cap.	number	ton/hr
A	0	0	0	0	0	0	0	0
B	0	0	14	92.7	4	127.6	18	220.3
CH	1	1.3	6	42.5	1	19.6	8	63.4
D	0	0	0	0	0	0	0	0
DK	3	7	4	27	0	0	7	34
E	1	2.5	4	30	2	64.2	7	96.7
F	6	16.9	20	131.75	13	378.75	39	527.4
I	0	0	6	54.7	2	39.9	8	94.6
L	0	0	0	0	0	0	0	0
N	13	12.75	0	0	0	0	13	12.75
NL	0	0	0	0	1	52.5	1	52.5
S	1	2.5	5	33.6	0	0	6	36.1
SF	0	0	1	10	0	0	1	10
UK	0	0	13	123.5	15	389.5	28	513
TOTAL	25	42.95	73	545.75	38	1072.05	136	1660.75

Dry scrubber

	<= 3 ton/hr		3 to 15 ton/hr		>= 15 ton/hr		total per country	
	number	total cap.	number	total cap.	number	total cap.	number	ton/hr
A	0	0	0	0	0	0	0	0
B	0	0	2	14.6	0	0	2	14.6
CH	0	0	0	0	0	0	0	0
D	1	3	0	0	3	109.5	4	112.5
DK	2	5.5	5	36	0	0	7	41.5
E	0	0	0	0	0	0	0	0
F	3	6	5	29	1	20	9	55
I	0	0	2	14.2	0	0	2	14.2
L	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	0
NL	0	0	1	12	0	0	1	12
S	1	0	4	31.95	4	111	9	142.95
SF	0	0	0	0	0	0	0	0
UK	0	0	0	0	0	0	0	0
TOTAL	7	14.5	19	137.75	8	240.5	34	392.75

Semi-dry scrubber

	<= 3 ton/hr		3 to 15 ton/hr		>= 15 ton/hr		total per country	
	number	total cap.	number	total cap.	number	total cap.	number	ton/hr
A	0	0	0	0	0	0	0	0
B	0	0	0	0	1	40	1	40
CH	0	0	1	13	1	15.2	2	28.2
D	0	0	3	31.6	9	395.1	12	426.7
DK	0	0	1	10	4	121.5	5	131.5
E	0	0	0	0	0	0	0	0
F	1	2.5	7	74	6	137	14	213.5
I	0	0	0	0	0	0	0	0
L	0	0	0	0	1	24	1	24
N	0	0	0	0	0	0	0	0
NL	0	0	0	0	0	0	0	0
S	0	0	0	0	0	0	0	0
SF	0	0	0	0	0	0	0	0
UK	0	0	0	0	0	0	0	0
TOTAL	1	2.5	12	128.6	22	732.8	35	863.9

Wet scrubber, 1-stage

	<= 3 ton/hr		3 to 15 ton/hr		>= 15 ton/hr		total per country	
	number	total cap.	number	total cap.	number	total cap.	number	ton/hr
A	0	0	0	0	0	0	0	0
B	0	0	1	11.2	1	27	2	38.2
CH	0	0	1	11.2	0	0	1	11.2
D	0	0	3	27.6	5	309.4	8	337
DK	3	7.8	5	40	0	0	8	47.8
E	0	0	0	0	0	0	0	0
F	0	0	5	36.5	5	220	10	256.5
I	0	0	2	20	1	25	3	45
L	0	0	0	0	0	0	0	0
N	0	0	4	39	1	20	5	59
NL	0	0	2	12.5	0	0	2	12.5
S	1	0	3	16.3	2	70	6	86.3
SF	0	0	0	0	0	0	0	0
UK	0	0	0	0	0	0	0	0
TOTAL	4	7.8	26	214.3	15	671.4	45	893.5

Wet scrubber, 2-stages

	<= 3 ton/hr		3 to 15 ton/hr		>= 15 ton/hr		total per country	
	number	total cap.	number	total cap.	number	total cap.	number	ton/hr
A	0	0	0	0	0	0	0	0
B	0	0	1	7.2	0	0	1	7.2
CH	0	0	13	112.3	6	189.8	19	302.1
D	1	3	3	25.7	14	538.4	18	567.1
DK	0	0	1	6.3	2	68	3	74.3
E	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0
L	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	0
NL	0	0	1	8	3	182	4	190
S	0	0	0	0	0	0	0	0
SF	0	0	0	0	0	0	0	0
UK	0	0	0	0	0	0	0	0
TOTAL	1	3	19	159.5	25	978.2	45	1140.7

Active cokes adsorption

	<= 3 ton/hr		3 to 15 ton/hr		>= 15 ton/hr		total per country	
	number	total cap.	number	total cap.	number	total cap.	number	ton/hr
A	0	0	0	0	2	48	2	48
B	0	0	0	0	0	0	0	0
CH	0	0	0	0	0	0	0	0
D	0	0	1	10	6	261.9	7	271.9
DK	0	0	0	0	0	0	0	0
E	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0
L	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	0
NL	0	0	0	0	2	182	2	182
S	0	0	0	0	0	0	0	0
SF	0	0	0	0	0	0	0	0
UK	0	0	0	0	0	0	0	0
TOTAL	0	0	1	10	10	491.9	11	501.9

Appendix C Waste composition, used for calculations

Appendix C

Removal efficiencies assumed for flue gas cleaning equipment

	dust	HCl	HF	SOx	Hg	Cd/Tl	rest	PCDD/F
dust remov.:ep/ff	98%	0%	0%	0%	10%	50%	80%	0%
dry scrub: d	80%	90%	80%	50%	30%	50%	70%	50%
semi-dry: s	80%	98%	90%	80%	40%	60%	80%	50%
1st wet: w1	80%	99%	95%	40%	80%	80%	90%	50%
2st wet: w2	90%	99.5%	99%	95%	90%	90%	95%	50%

NOTE: These removal efficiencies are not based on what is technically possible with this equipment, but on what is achieved in general in practice.

The raw flue gas emissions were calculated with mass balances for a standard waste composition. With an air factor of 1.8 and a capacity of 7 ton/hr, this results in:

flue gas wet	37228	Nm3/hr
H2O-conc.	14.89	vol%
flue gas dry	31685	Nm3/hr
O2-conc.	9.6	vol% on dry

Component	mg/m3 **(actual, not on 11% O2)**	mg/Nm3 **(11% O2)**
dust	5360	4720
HCl	1205	1060
HF	0.23	0.2
SOx (as SO2)	306	270
Hg	0.45	0.4
Cd+Tl	0.57	0.5
Rest	34.7	31
PCDD/F (assumed) ng I-TEQ/Nm3	-	15

Rest = Sb,As,Pb,Cr,Co,Cu,Mn,Ni,V,Sn

The PCDD/F-concentration in the raw flue gas was estimated to be 15 ng I-TEQ/Nm^3 at 11% O_2.