TECHNICAL AND ECONOMIC ASSESSMENT OF ENERGY CONVERSION TECHNOLOGIES FOR MSW

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by

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ABSTRACT

In this report, an attempt has been made to provide a description, and technical and economic assessments, of the novel thermal processes for the treatment of MSW, which are relevant to the emerging British market. This is not an easy task in that the majority of the relevant processes are under development or at best in the demonstration phase. Only a few of the relevant technologies can be regarded as being in full commercial operation, and none are in commercial operation in Britain.

Brief technical descriptions of seven novel processes are given in this report, and five technologies have been selected for more detailed comparison, on the basis of their development status and likely relevance to the emerging British market, viz:

- The Mitsui R21 Technology,
- The Thermoselect Process,
- The Nippon Steel Waste Melting Process,
- The Pyropleq Process, and
- The Compact Power Process.

All of these technologies are based on pyrolysis and/or gasification of the MSW or shredded MSW as the initial element of the thermal treatment. In the case of the Thermoselect process, a cleaned syngas, suitable for use as a fuel for a gas turbine, a gas engine or a boiler is the primary product. In all other cases, the pyrolysis/gasification process is coupled with a combustor with energy recovery in a steam boiler.

Three of the processes, i.e. the R21 process, the Thermoselect process and the Nippon Steel process provide a fused ash product, which is suitable for recycling. The Pyropleq and Compact Power processes produce bottom ash and fly ash discard streams, which are sent for landfill disposal after suitable treatment.

The technical comparison of the candidate processes has been made under the following subject areas:

- The overall technical concept,
- The energy balance and the requirement for supplementary fuels or specific reagents,
- The environmental performance in the context of the requirements of the new EC Directive on the incineration of waste, and
- The overall technical and commercial status of the technologies.

In general terms, those processes which do not require oxygen or a supplementary fuel under normal operating conditions, and which provide a fused ash product, are preferred technically, although these technologies tend to be more complex, have lower net power export efficiencies and higher capital costs than the other processes.

The provision of a meaningful comparison of the economics of the novel processes is a very difficult task, in that none of the relevant processes is in commercial operation in the British market, and this means that the availability of comparative cost information is limited.

EXECUTIVE SUMMARY

Objectives of the Project

In this Report, an attempt is made to provide a description and technical and economic assessments of the novel thermal processes for the treatment of municipal solid waste (MSW), concentrating on those processes which are likely to be relevant to the emerging British market over the next 5-10 years. These processes are based on the pyrolysis or gasification of the waste, and the majority are currently under development or, at best, are in the demonstration phase. Only a relatively small number can be regarded as being in full commercial operation, and none are in commercial operation in Britain.

Technical Background

It is clear that the disposal of large quantities of mixed solid waste materials to landfill is not a sustainable solution. This has been recognised at the highest political levels, and the EC Landfill Directive (1999/31/EC) has set progressive targets for reductions in the quantities of biodegradable municipal wastes that can be sent for landfill disposal. In Britain, the consequence of compliance with the Landfill Directive will be substantial investment in the waste management infrastructure. It is also clear that the thermal processing of MSW, with energy recovery, will play an increasing role, as an alternative to the landfill disposal of the mixed waste materials, which will inevitably remain after waste minimisation, recycling and composting activities.

In Britain, waste incineration plays a relatively small role in waste management, with less than 10% of the current MSW arisings being processed in this way. All of the current MSW incinerator stock is based on conventional mass burn or, in one case, fluidised bed combustion. There are, however, a number of novel, thermal processing technologies for MSW, based on pyrolysis or gasification of the waste, which may provide significant technical and environmental advantages over conventional incineration.

Pyrolysis processes involve the exposure of organic materials to temperatures in excess of 400°C in the absence of oxygen. The principal products of the process are:

- A combustible pyrolysis vapour,
- Condensable organic liquids, and
- A solid residue, containing the unreacted char material and the inorganic fraction of the waste.

The relative proportions of these products depend on the nature of the feedstock and the process conditions. It is important to note that the waste has to dry before the pyrolysis reactions can begin to occur and that both the drying and pyrolysis processes are endothermic, ie an external source of heat is required to sustain the process.

Gasification processes involve the reaction of carbonaceous feedstocks with an oxygen-containing reagent, usually oxygen, air, steam or carbon dioxide, or a combination of these, at elevated temperatures. The quantity of oxidant supplied is much lower than the stoichiometric quantity required for combustion of the feedstock. Most industrial gasification processes are thermally self-sustaining, ie little or no external heat supply is required. The principal products of gasification processes are a fuel gas, which usually contains condensable tars and liquids, and a solid residue material, which contains both unreacted char and the inorganic components of the feedstock.

The majority of the industrially important pyrolysis and gasification processes were originally developed for the processing of coal, however they are increasingly being applied to a variety of waste materials.

There is a growing perception within the waste management industry that the more novel thermal processes, based on pyrolysis and gasification of MSW, will play an increasing role in the British market over the short-medium term future. It is timely, therefore, to carry out a critical technical, environmental and economic assessment of those novel processes, which are likely to be relevant to the British market. This is the principal objective of the work described in this Report.

Technical Description of the Selected Novel Thermal Processes for MSW

MSW is a highly variable and heterogeneous multi-component material, which varies with both time and location. It is a poor quality fuel, with relatively high moisture and ash contents, and a relatively low calorific value, compared to most other solid fuels of industrial interest. MSW has relatively low nitrogen and sulphur contents, but has a significant chlorine content.

The characteristics and the variability of MSW have a significant impact on its behaviour as a fuel in combustion and other thermal processes. In addition to its variability, MSW is notoriously difficult to handle and to feed in a controlled manner to incineration and other equipment. This is reflected in the design of MSW handling and feeding systems, and has a knock-on effect on the difficulties encountered in the control of the process conditions in conventional incinerators and other plant. MSW is also a high slagging and fouling fuel, ie it has a high propensity to the formation of fused ash deposits on the internal surfaces of furnaces and high temperature reactors, and of bonded ash deposits on heat exchanger surfaces. The products of the thermal processing of MSW are also very aggressive, ie there is a tendency for accelerated metal loss of reactor and heat exchanger components due to erosive and corrosive attack.

Overall, therefore, it is clear that MSW is a very difficult fuel and this should be reflected in the design of the fuel handling and feeding systems, the furnace or pyrolysis/gasification reactor and the heat recovery equipment in conventional incineration plant and the more novel thermal processes.

The great majority of incineration plants for MSW, which are in operation around the world, are based on mass burn incineration systems. The technology is mature and robust, and the technical/environmental performance and the economics of mass burn incineration are well understood. When considering the novel thermal processes for MSW, the question arises, therefore, as to what advantages these novel processes can provide in comparison to conventional incineration.

The most basic reason for serious consideration of the use of pyrolysis/gasification processes for MSW is that there has been increasing technical, environmental and public concern about the performance of conventional incinerators. The combustion of a poor quality and variable fuel, such as MSW, on a grate is far from ideal. The quality of the flue gases is such that special arrangements for its further processing are required, viz

- The provision of a secondary combustion chamber has to be made to ensure that high efficiency gas phase incineration is achieved.

- The heat recovery boiler has to be specially designed to handle the aggressive flue gases and to avoid excessive ash deposition, and

- Significant investment in back-end, flue gas cleaning equipment is required to meet the statutory consent limits for the emission of pollutant species.

There are also concerns about the quality and the disposal of the solid residues, and about the total releases of Dioxins, from conventional incineration plants. In an increasing number of countries, the ash residues require further processing before they can be sent for landfill disposal.

It is fair to say, therefore, that the technical objectives of the developers of the novel thermal processes are three-fold, viz:

- To increase the scope for the recovery and recycling of the relevant components of the mixed wastes, and to improve the quality of the recycled materials,

- To simplify, and reduce the costs of the flue gas clean-up systems, compared to those applied to conventional incinerators, and

- To reduce the quantity, and improve the quality, of the solid discards from the thermal treatment processes that have to be sent for landfill disposal.

The thermal processes were selected for study on the basis of their technical approach and their development status, with an emphasis on those processes that have a high degree of innovation, and that are commercially available or are at least in the demonstration phase. Seven processes were selected for study, viz:

- The **Mitsui R21 process**, which is a close-coupled pyrolysis-high temperature combustion system, incorporating the recovery of ferrous and non-ferrous metals and the production of a fused ash product. This technology is now fully commercial in Japan.

- The **Thermoselect process**, which is a combined pyrolysis-high temperature gasification process, generating a clean fuel gas, with recovery of both the ash and metals in fused forms. There are two demonstration plants, based on the Thermoselect process, in Germany and Japan

- The **Ebara TwinRec process**, which is based on a revolving fluidised bed gasifier, with the product fuel gas fired in a cyclone combustor, operated as a slag tap. This technology is currently being marketed for the processing of more consistent, higher calorific value wastes, and not for MSW.

- The **Von Roll Recycled Clean Product (RCP)** process is based on gasification of the waste on a grate, with high temperature combustion of the pyrolysis vapours in a high temperature combustor, operated as a slag tap. There is a demonstration plant based on the Von Roll RCP process in Bremerhaven, Germany, however Von Roll are currently focussing on the marketing of the RCP process for higher calorific value wastes.

- The **Nippon Steel** process is based on the pyrolysis/gasification of the waste with coke in a vertical shaft furnace, with removal of the ash and metals as a slag. The product gas is burned in a downstream furnace, after high temperature dust removal. The Nippon Steel process is fully commercial in Japan.

- The **Pyropleq** process, is based on low temperature pyrolysis of the MSW with high temperature combustion of the product gas, after high temperature dust collection. There is a small plant in Burgau in Germany, based on this technology, which has been in operation for more than ten years. The process is currently being marketed in Britain by WasteGen UK Ltd.

- The **Compact Power** process, is based on the high temperature pyrolysis of the MSW, with fluidised bed gasification of the char residue. The product gas is burned in a high temperature furnace. A demonstration plant, based on this technology has been built in Avonmouth, near Bristol.

In the Report, technical descriptions of all of these processes are provided under the following subject areas:

- The process flow diagram,

- The mass and energy balances for the process, and

- The commercial status of the process.

Technical and Environmental Comparison of the Novel Processes

Of the processes described, five were selected for more detailed technical/environmental comparison, on the basis of their relevance to the British market, viz:

- The Mitsui R21 process,
- The Thermoselect process,
- The Nippon Steel process,
- The Pyropleq process, and
- The Compact Power process.

All of these processes are based on the pyrolysis or pyrolysis/gasification of the MSW, in fixed bed or rotary kiln reactors. In all of the successful processes for MSW, the reactors are large and have relatively long residence times. This provides some damping effect on the variability of the fuel, and hence the heat input to the system, and permits stable operation of the process. One of the key weaknesses of fluidised bed reactors for highly variable fuels is that they have a relatively small inventory of fuel in the bed, and have difficulty in the maintenance of stable operating conditions.

In all cases, the MSW pyrolysis process requires an external heat source. In the case of the Nippon Steel process, this is provided directly by the gasification of coke. In all other cases, the heat is provided indirectly, using hot, clean air, in the Mitsui R21 process, or recycled flue gases, as in the Thermoselect, Pyropleq and Compact Power processes. Intrinsically, the use of hot air has a number of attractions in that combustion flue gases, and particularly those which have a significant HCl concentration, tend to be highly corrosive, and there may be a tendency for the formation of ash deposits on heat exchanger surfaces. Hot, clean air will be much less aggressive in this regard.

The further processing of the pyrolysis vapour/syngas is one of the key differences between the processes. The Thermoselect process is very different from the others in that the syngas is cleaned, and can be used as a fuel for a boiler, gas turbine or gas engine, or can be used for other purposes. The Thermoselect process clearly has a degree of flexibility in this regard that the other processes do not permit. It should be noted, however, that the cleaning and cooling of the syngas does present a number of technical challenges.

All of the other processes involve the firing of the pyrolysis vapours in a combustor, with heat recovery from the hot flue gases in a purpose-designed steam boiler. The final steam conditions in all of the processes are 400°C and

40 bar, which is not untypical of those that apply in modern, conventional MSW incinerators. The steam is used for the production of heat and/or power, for utilisation within the plant and for export.

All of the novel processes have a requirement for a supplementary fuel for start-up, shutdown and emergency situations, however a number of the processes also have specific requirements under normal operating conditions, viz:

- The Thermoselect process has a requirement for both oxygen and natural gas for the gasification/ash melting reactor,
- The Nippon Steel process has a requirement for both oxygen and coke for the gasification/ash melting process,
- The Compact Power process has a requirement for a supplementary fuel to sustain high temperatures in the pyrolysis vapour combustion chamber.

The R21 and Pyropleq processes have no oxygen or supplementary fuel requirements under normal operating conditions. This is a significant environmental advantage, and will be reflected in the operating costs of these processes.

All of the processes have a requirement for gas cleaning reagents. The Thermoselect process involves extensive cleaning of the pyrolysis gas, with the gas cleaning reagent requirements depending on the further gas processing systems.

All of the other processes have fairly similar clean-up systems for the combustion flue gases. In general, these include particulate collection and acid gas scrubbing with lime or sodium bicarbonate. Some systems will require SNCR systems for NO_x emission control, and activated carbon additions for the control of mercury and dioxin emissions, depending on the requirements of the environmental regulations.

There are considerable difficulties in providing a meaningful comparison of the energy balances and power outputs for the novel processes. A number of the processes have insufficient commercial operating experience, and have not been optimised in this respect. The power output is very dependent on the assumptions made on the MSW quality and the plant throughput. There are also significant differences between processes, eg whether or not they require supplementary fuels or oxygen, and whether or not they generate a fused ash residue, which have a significant impact on the net power output. All of these factors have to be taken into account in a proper comparison between the different processes.

In very broad terms, the novel technologies can be divided into three groups in this regard, viz:

- The Thermoselect process, which has a relatively high power export level, per tonne of MSW, albeit with a support fuel,

- The Pyropleq and Compact Power processes, which do not produce a fused ash, and can export around 450-550 kW_e per tonne of MSW, and

- The R21 and Nippon Steel processes, which produce a fused ash and can export around 400 kW_e per tonne of MSW.

- Conventional mass burn incineration plants, without ash melting systems, generally export around 500-600 kW_e per tonne of MSW.

One of the key points of comparison between the novel technologies and the conventional mass burn incinerators is their environmental performance. All of the relevant processes, including mass burn incinerators, are capable of compliance with the requirements of the new EC Incineration Directive (2000/076/EC), as regards their gaseous and gas-borne emissions, with suitable investment in flue gas cleaning equipment.

The major differences between processes are in the quality of the solid residues from the processes, and the utilisation/disposal requirements for these residues, and in the total releases of Dioxins from the processes. Those processes, such as the Mitsui R21, the Thermoselect and the Nippon Steel processes, which generate a fused ash product, have particular environmental advantages. For those novel processes, which do not produce a fused ash, these may be significant issues, with regard to compliance with the required operating standards in a number of respects. There may be a requirement for further processing of the ashes and other residues, prior to disposal.

In terms of their environmental performance, the Mitsui R21 process, the Thermoselect process and the Nippon steel process have distinct advantages over the other novel processes, and represent a step change improvement over conventional mass burn incineration. It should be noted, however, that both the Thermoselect and Nippon Steel processes have both oxygen and supplementary fuel requirements, and that the R21 and Nippon Steel processes have lower power export levels.

In terms of their overall technical status, the Nippon Steel and the Mitsui R21 processes can be regarded as being fully commercial in the Japanese market, however no plants have been sold outside Japan in either case. There is one small plant in Germany, based on the Pyropleq process, which has been in commercial operation for more than ten years, however this process has not, as yet, been replicated successfully anywhere else. The Thermoselect and Compact Power processes are still in the demonstration phase.

The Economic Comparison Of Conventional Incineration, and the Novel Thermal Processes for MSW

The current capital and operating costs of conventional incineration plants for MSW are reasonably well understood, particularly for plants processing more than 100,000 tonnes of MSW per annum. In the Report, the declared capital and operating costs for existing plants in Britain have been used as the basis for the estimation of the costs of future incineration plants over the size range 70,000-400,000 tonnes of MSW per annum. These costs have been used as input to a business model of project funded waste incineration projects, to provide estimates of the gate fees for MSW processing over this range of plant sizes. The results of this exercise have indicated that there are significant economies of scale, with the gate fees increasing from around £30 per tonne to more than £80 per tonne over this size range.

It has proved to be very difficult to prepare similar cost estimates for the novel thermal processes in Britain. By their very nature, these processes are new to the market. Most of them are in the development or demonstration phase, and no commercial plants based on the novel technologies have been built to date in Britain.

1. INTRODUCTION

It has been apparent for some time that the disposal of very large quantities of mixed solid waste materials to landfill is not a sustainable practice, and is damaging to the environment. This has been recognised at the highest political levels in Europe, and the EC Landfill Directive (1999/31/EC), which came into force in July 1999, has set progressive targets for the reduction of the quantities of biodegradable municipal wastes that can be sent to landfill. If these targets are to be met, it is clear that substantial tonnages of MSW in Britain will have to be diverted from landfill over the next 20 years. Compliance with the EC Directive means that the development of waste management infrastructure is no longer a matter of government policy, subject to the prejudices of the incumbent regime, but is now a matter of legal obligation. The under-investment in the infrastructure, which has been a feature of government policy over the past 20 years, can no longer apply. This has been recognised by the current British government and, as a result, Waste Strategy documents have recently been issued for England and Wales, Scotland and Northern Ireland, which outline waste management policy over the next 20 years. One of the key elements of these documents is the development of waste management strategies, which ensure compliance with the Landfill Directive and other obligations.

In this context, it is clear that there will be substantial investment in waste management infrastructure in Britain over the next 20 years. The installation of energy from waste facilities will play an increasing role in waste management and disposal, as an alternative to landfill of the substantial quantities of mixed waste materials, which will inevitably remain after waste minimisation, recycling and composting activities.

The current situation in Britain is that less than 10 % of the total arisings of MSW is sent for incineration. The MSW incinerators currently in operation in Britain are listed in Table 1. All of these incinerators are conventional combustion plants either mass burn incinerators, fluidised bed combustors (Dundee) or refuse-derived fuel plants, with combustion of the RDF in stoker-fired boilers.

In addition to the conventional combustion-based incineration technologies, based either on moving grate or fluidised bed combustors, there are a number of more novel thermal processing technologies being developed. A number of these are currently in the demonstration phase or in the early stages of commercialisation. The majority of these more novel technologies are based on the pyrolysis or gasification of the MSW.

Pyrolysis involves the thermal processing of the organic materials at temperatures in the range 400-800°C in the absence of oxygen. The more important processes that occur during industrial pyrolysis processes, ie the drying of the waste and the release of volatile components of the carbonaceous materials, are both endothermic processes, and all pyrolysis processes require an external source of heat.

The principal products of the pyrolysis of waste materials are a pyrolysis vapour, condensable liquids and a solid residue, which contains unreacted char and the residues of the inorganic components of the feedstock. The relative proportions of these products depend on the nature of the feedstock and the pyrolysis process parameters. In general terms, pyrolysis processes operating at lower temperatures produce higher proportions of liquids, whereas higher temperature processes produce a higher proportion of gaseous products.

Gasification processes involve the reaction of carbonaceous feedstocks with an oxygen-containing reagent, usually oxygen, air, steam or carbon dioxide, generally at temperatures in excess of 800°C. The quantity of oxidant supplied is much lower than the stoichiometric quantity required for combustion of the feedstock.

The principal products are a fuel gas, which usually contains condensable liquids and tars, and a relatively inert char. With most industrial gasification processes, the intention is to transfer the energy content of a solid fuel into the gas phase, to provide a gaseous fuel or, in some applications, a chemical feedstock.

Most of the industrially important gasification and pyrolysis technologies were originally designed for coal, however they have been increasingly applied for the processing of waste materials over the past 10-20 years, principally because of concerns about the environmental performance of conventional incineration technologies. There is a perception within much of the waste management industry that the application of the more novel technologies will play an increasingly important role in the British market over the next few years.

This report has been prepared as the major deliverable item of a project entitled ‘Comparative technical and economic assessment of energy conversion technologies for MSW’, carried out with financial support from DTI. The principal objective of the project is to perform a technical and economic assessment of the conventional mass burn incineration technologies and of a number of the more novel energy conversion technologies for MSW. The assessment covers the range of plant sizes from 70,000-400,000 tonnes of MSW p.a., however there is particular emphasis on the lower end of this size range, since this is most relevant to the novel technologies.

It should be recognised that the author of this report is an employee of Mitsui Babcock and that the company have a commercial interest in the Mitsui R21 process, one of the novel thermal processes covered in this report. In the performance of the work and in the preparation of the technical and environmental assessments of the competing technologies, however, every effort has been made to ensure that the assessments of individual processes, and the sentiments expressed in the report, have been made on a sound technical basis and are accurate and balanced.

2. TECHNICAL DESCRIPTION OF THE THERMAL PROCESSING TECHNOLOGIES FOR MSW

2.1 The Nature of Municipal Solid Waste (MSW)

Municipal solid waste (MSW) is a highly variable and heterogeneous multi-component material, which varies both seasonally and geographically. A listing of relevant data, which provides information on the composition of British MSW, is presented in Tables 2 and 3. The Category Assay data in Table 2 provides a partial listing of the major constituents of the waste, however it is clear that the majority of the categories in the list are themselves multi-component materials.

The calorific value or heat content of the MSW is provided by a number of the materials listed in the category assay, however the major contributions are from the paper and board, the plastics and the textiles. The Proximate and Ultimate analysis data in Table 3 indicate that the MSW is a poor fuel, with relatively high moisture and ash contents, and a relatively low Gross Calorific Value, compared to most other solid fuels of industrial interest. The material has relatively low nitrogen and sulphur contents, but has a significant chlorine content.

The characteristics and the variability of the MSW as a fuel have a significant impact on its behaviour as a fuel in combustion and other thermal processing systems. In addition to the variability in composition, MSW is notoriously difficult to handle, and to feed in a controlled manner to incineration and other equipment. This is reflected in the design of MSW handling and feeding systems, and has a significant knock-on effect on the difficulties encountered in the control of the combustion conditions in conventional incineration plant. MSW is also a high slagging and fouling fuel, i.e. it has a high propensity to form fused ash deposits on the internal surfaces of furnaces and high temperature reactors, and to form bonded fouling deposits on heat exchanger surfaces.

The products of the combustion of MSW are also very aggressive, in that the flue gases are erosive and the relatively high levels of chloride-containing species in the flue gases can lead to high rates of metal wastage of heat exchange tube surfaces due to high temperature corrosion.

Overall, therefore, it is clear that MSW is a very difficult fuel, and this is reflected in the design of MSW incinerators, and of the associated heat recovery and other equipment.

2.2 Conventional Mass Burn Incinerators for MSW

The great majority of incineration plants for MSW, in operation throughout the world, are based on mass burn combustion systems.

A schematic diagram, which illustrates the overall process flow for a conventional mass burn incineration plant with heat recovery and power generation, is reproduced in Figure 1. In this system, the MSW is incinerated in a moving grate combustor, fitted with a combustion air supply and bottom ash pit. The hot flue gases from the combustor pass through a radiant furnace and a convective boiler section, where high pressure steam is generated, and supplied to the turbo-generator. The cooled flue gases then pass through the gas clean-up section before being exhausted to atmosphere via the chimney.

The basic principles of the mass burn combustor are illustrated in Figure 2. The raw waste is introduced from a feed hopper, and is usually fed by a ram feeder system to the top of the grate, where it is immediately exposed to radiant heat from the furnace. The processes that occur as the MSW is passed along the grate are as follows:

- The drying of the wet waste occurs, with the heat supplied by radiation from the furnace. There is commonly a refractory-lined ignition arch over the front section of the grate to aid this process.

- The heating of the dried waste to a temperature at which the release of volatile components can begin to occur,

- The devolatilisation of the MSW, and the combustion of the volatile species in the flame above the bed of waste occur, with the combustion air supplied both underneath and above the grate.

- When the devolatilisation process is complete a char material is left, and this material burns out with air supplied beneath the grate. A refractory-lined char burnout arch is often installed over the char burnout zone to assist this process.

- On completion of the char burnout process, the ash residue fall over the end of the grate into the ash pit.

A number of grate designs have been employed for MSW combustion, however modern plants are commonly based on two basic designs, viz:

- **The stepped, inclined grate**, which uses moving bars or rockers to move the waste down the grate, which is usually divided into a number of sections.

- **The roller grate**, which consists of a number of adjacent drum or roller grates, arranged in a stepped formation to provide an inclined surface down which the burning waste moves. The drums or rollers rotate slowly in the direction of waste movement.

In both cases, the burning MSW is moved slowly down the inclined grate and the presence of the steps or the action of the rollers provides a tumbling motion which helps to mix the waste and aid the drying, devolatilisation and char burnout processes. The combustion air is supplied both underneath and above the grate. The primary or undergrate air is supplied from compartmented windboxes located under the grate, to allow control over the air distribution to the different sections of the grate. The secondary air is supplied through nozzles located in the furnace walls above the grate. Since the MSW has a relatively high volatile matter content, a high level of secondary air is required to aid good mixing and combustion of the volatiles released from the fuel bed. The refractory ignition and char burnout arches, and the lower furnace, are also designed specifically to maintain high gas temperatures, and to encourage mixing of the combustion gases released from the fuel bed. The lower furnaces of modern incinerators are usually lined with a refractory material, commonly silicon carbide, to provide protection of the furnace tubes from the highly erosive and corrosive conditions that apply in the region above the grate.

Modern MSW incinerators have a large radiant furnace, normally of membrane tube construction, and with silicon carbide tile protection on the gas side in the high temperature zone. The radiant furnace is required for two reasons:

- There is a legislative requirement for the combustion gases, after the last injection of combustion air, to be maintained, at all times, at temperatures in excess of 850°C for two seconds and in the presence of 6% oxygen. This requirement is intended to ensure good gas phase combustion to minimise the generation of dioxin precursor compounds, and hence minimise the potential for dioxin synthesis within the boiler.

- There is a technical requirement to reduce the flue gas temperatures at the entry to the convective section of the boiler to levels around 700°C or lower to avoid the formation of excessive and tenacious ash deposits on the heat exchange surfaces.

There are a number of additional constraints on the design of the radiant furnace, e.g.

- The design flue gas velocities within the radiant furnace are controlled to minimise particulate carryover from the first furnace pass, and

- The furnace passes must be designed to avoid dead zones and regions of very low gas velocity, and to make the most effective use of the membrane heat exchange surface.

- The membrane wall tube pitching is chosen to ensure adequate cooling of the membranes, and

- The gas side surfaces of the radiant furnace are prone to ash deposition and adequate provision of on-line cleaning must be made. Conventional steam wallblowers are normally used to clean the membrane wall panels, and retractable steam blowers are used for the screen tubes.

- The screen tubes are usually arranged in parallel with wide cross and back pitches to further reduce the tendency for the accumulation of ash deposits.

There are a number of boiler arrangements, which have been used for MSW incineration plants.

The radiant pass can be of one, two or three pass arrangement, and the convective section is usually a tail end arrangement or is arranged vertically. The convective section normally comprises a number of superheater banks, and an economiser. The requirement for an evaporator bank is dependent on the total heat absorption in the furnace and the convective section enclosures, and the economic case for a dedicated evaporator bank against the use of additional economiser surface. In many large, modern MSW incinerators with large radiant furnaces, there is no separate evaporator bank, and all of the evaporative duty is performed in the economiser, and the furnace and boiler enclosure surfaces.

The boiler final steam conditions for waste incineration plants are conventionally around 400°C and 40-70 bar. The relatively low steam temperatures are necessary to avoid excessive rates of tube metal loss in the final superheater, due to high temperature corrosion. MSW is a particularly aggressive fuel in this regard, due to the high chlorine levels and relatively low sulphur levels in the fuel. Restriction of the final steam conditions in this way obviously has an impact on the overall electricity generation efficiency, however past experience of incineration plants, which have been designed with higher final steam temperatures, has indicated that serious loss of availability and substantial pressure part replacement costs have resulted.

The design of the convective pass also reflects the difficult nature of the products of combustion of MSW. As stated above, the flue gas temperatures at the entry to the convective pass are reduced to values below 700°C to avoid excessive ash deposition, and flue gas velocities are controlled to minimise the wastage rates of the tubes due to particle impact erosion.

The boiler convective section has to be designed for a highly fouling fuel and for low flue gas velocities. This has implications for both the bank arrangement and the tube pitching. Conventional steam sootblowing is often employed to clean convective banks in a vertical arrangement, whereas mechanical rapping devices are usually preferred for a tail end boiler arrangement.

With the latter, the erosion problems that are commonly associated with the overuse of steam sootblowers are avoided, and the overall steam requirement for sootblowing is reduced.

Rapping techniques do, however require that the convective tube banks are specifically designed for that purpose. It is also of importance that adequate provision of ash hoppers under the convective banks and the economiser is made, to allow satisfactory collection and removal of the ash material. The maintenance of clean surfaces in the boiler convective section is also important for the minimisation of dioxin synthesis within the boiler.

The combustion gases exit the boiler, and enter the flue gas clean-up system prior to exhaust to the atmosphere. A number of the constituents of the flue gases are prescribed pollutant species under the Integrated Pollution Control (IPC) Regulations. The emission of these species is controlled under the authorisation to operate the incineration plant from the relevant environmental regulation authority.

In addition to the gaseous and gas-borne pollutant species, there are controls on the releases of pollutant species to other media, and general operating standards and guidance on good practice throughout the plant. The current requirements in Britain are described in a document issued by the Environment Agency in October 1996, although it should be noted that an Incineration Directive, which describes more stringent controls, has recently been issued by the European Commission.

The current British operating standards are described in:

Processes Subject to Integrated Pollution Control
IPC Guidance Note
Series 2 (S2) – Waste Disposal and Recycling Sector
S2 5.01: Waste Incineration – and Energy from Waste Plants for the Following Wastes:
Chemical, Clinical, Municipal, Sewage Sludge, Animal Carcasses and Drum residues.
The Environment Agency, (October 1996).

The environmental performance of conventional MSW incineration plants and of the more novel thermal processes for MSW will be discussed in more detail below.

2.3 The Novel Thermal Processes for MSW

As discussed in Section 1 above, the majority of the novel thermal processes for MSW, which can be applied as alternatives to conventional incineration processes, are based on pyrolysis and/or gasification of the waste.

The question arises, of course, as to what advantages these processes bring in comparison to conventional combustion-based processes.

The most basic reason for serious consideration of the use of gasification/pyrolysis processes for the treatment of MSW and other wastes in recent years, is that there has been increasing technical, environmental and public dissatisfaction with the performance of conventional incineration processes, particularly for MSW. In Britain, there is clearly considerable justification for this view. Prior to the Environmental Protection Act 1990, the environmental performance of many of the MSW incineration plants in operation in Britain was very poor. The majority of these plants were closed during the 1990's, and those that remained in operation underwent significant modification and improvement, particularly in terms of their environmental performance. The new plants, which were constructed during the 1990's, were designed, and are operated, to much higher standards.

The problem remains, however, that the combustion of a poor quality and heterogeneous material like MSW, on a grate or in a fluidised bed combustor, is far from ideal. The quality of the flue gases is such that special arrangements for its further processing are required, viz:

- The provision of a secondary combustion chamber has to be made to ensure that high efficiency gas phase incineration is achieved.
- The heat recovery boiler has to be specially designed to handle the aggressive flue gases and to avoid excessive ash deposition.
- Significant investment in back end, flue gas clean-up equipment is required to meet the consent limits for the emission levels of the prescribed pollutant species.

There are also concerns about the quality and disposal of the solid residues and about the total releases of Dioxins from conventional incineration plants.

All of these issues, of course, add significantly to both the capital and operating costs of incineration plants. It is fair to say, however, that conventional MSW incineration is the most popular technology for the thermal processing of MSW at the present time. It is a mature and well-established technology and, as such, is regarded by the waste management industry as representing low technical and financial risks.

It is clear, however, that the public and the environmental regulation authorities in a number of countries increasingly regard the new and emerging technologies as representing a significant improvement on conventional incineration, and it may only be a matter of time before these technologies begin to replace conventional incinerators for new projects. This has begun to happen already in Japan, for instance, where the waste management infrastructure is more advanced than that in Britain..

The novel thermal processes for MSW and other waste materials are based on concepts that are not new, but have been in use for many years. Pyrolysis and gasification processes have been in use for centuries, principally for coal and wood, and there was significant development of these processes, applied to coal, in response to the oil price increases in the 1970's and 1980's.

The novel element of the emerging technologies is the application of pyrolysis and gasification to more complex waste materials and the technical objectives of the process developers is three-fold, viz:

- To increase the scope for the recycling and re-use of the relevant components of mixed wastes, and to improve the quality of the recycled products,
- To simplify and reduce the cost of the flue gas clean-up systems, compared to those applied to conventional incineration plants, and
- To reduce the quantity and improve the quality of the solid discards from the thermal treatment processes that require disposal to landfill.

In this Section of the Report, the technical and environmental aspects of a number of the leading novel thermal processing technologies for MSW will be described in some detail. These processes have been selected on the basis of their technical approach and their commercial status, with an emphasis on those processes, which have a high degree of innovation, and which are commercially available or at least are in the demonstration phase.

2.3.1 The Mitsui R21 Process

The concept of the R21 process was developed by Siemens in Germany during the 1980's, and has been further developed and commercialised, under a licence agreement with Siemens, by Mitsui Engineering and Shipbuilding (MES) in Japan, during the 1990's. MES have made significant improvements to the design and operational philosophy of the process, and have significant experience of the system, gained through the operation of a 24 tonne per day pilot unit, sited initially in Yokohama and subsequently in Chiba. MES received their first order for a commercial plant in July 1997, for the

Yame Seibu Clean Centre near Fukuoka, which is situated on Kyusyu Island in Southern Japan. The client's requirements included:

- MSW thermal processing facilities, with heat recovery and power generation, to handle an MSW throughput of 220 tonnes per day (two lines at 110 tonnes per day), and
- Facilities for the treatment of bulky waste with a throughput of 50 tonnes delivered over 5 hours per day. These facilities include ferrous metal recovery, with the residue being fed to the MSW thermal processing plant.

The plant was commissioned over the period December 1999 to February 2000, and underwent a series of performance and guarantee trials during February and March 2000. The plant was accepted by the client and was handed over for commercial operation at the end of March 2000.

The R21 Process Flow Diagram

The Yame plant is based on Mitsui R21 technology. A process flow diagram is reproduced in Figure 3, and a listing of the major plant items is presented in Table 4.

After recovery of recyclable materials from the bulky waste, the bulky waste residue is shredded and both the MSW and the bulky waste residue are delivered to the **refuse bunker**.

The waste is recovered by crane and fed to a biaxial shear crushing unit, which reduces the waste to a topsize of around 200 mm. The crushed waste is then fed, via the waste conveyor, to the inlet hopper above the screw feeder to the **pyrolysis drum.**

The crushed waste undergoes drying and low temperature pyrolysis in a rotary drum. The MSW is heated indirectly by hot air, which passes through a number of heat transfer tubes, arranged along the length of the drum. The drum is very effectively sealed against air ingress, with the result that the metals, both ferrous and non-ferrous are unfused and non-oxidised, and can be recovered in a clean form for recycling.

The total residence time of the waste in the pyrolysis drum is of the order of one hour. The system is relatively insensitive to variations in the quality of the waste feed, allowing stable operation of the downstream equipment, principally the high temperature combustor, the heat recovery boiler and the flue gas clean-up equipment.

The products of the pyrolysis process are:

- The pyrolysis gas, which is carried forward directly to the high temperature combustor, and

- The solid residue, which comprises char, inorganic solids and metals.

The solid residues from the pyrolysis drum are separated from the pyrolysis gas in a purpose-designed unit, and passed to the **solids handling facility**. The hot solids are cooled and then sorted in a series of screens. The ferrous and non-ferrous metals are recovered for recycling, in a clean, unfused and non-oxidised form, which finds ready markets. After metals recovery, the solid residues, which contain both combustible char and inert material, are crushed to a topsize of 1 mm, and are conveyed pneumatically to the **high temperature combustor**.

The pyrolysis gas and the crushed material from the solids handling facility are co-fired in the high temperature combustor. This is operated as a cyclone furnace, with the ash particles being encouraged to attach to the furnace walls.

The combustor operates at temperatures in excess of 1300°C, to ensure complete fusion of the ash, and a continuous flow of molten ash is maintained down the furnace walls and into the slag tap unit at the bottom.

The pyrolysis gas and the crushed solids are reasonably good quality and consistent fuels, and very good, stable combustion conditions are achieved, without support fuel, with very low CO concentrations, at oxygen concentrations around 3.5% (excess air ratio around 1.2). The very good combustion conditions ensure that the generation of dioxin precursor compounds is minimised.

The fused ash flows down the furnace walls and through the **slag tap** at the bottom, where it is immediately quenched in water to produce an inert, granular glassy material. Since metallic items have been removed with high efficiency in the solids handling facility, the slag is largely free of metals and is of high quality. This slag material is sold as a road construction material.

The combustion gases pass from the furnace exit to the **high temperature airheater**. This unit generates the hot air, at around 520°C, which is used for the indirect heating of the pyrolysis drum. The air is circulated in a closed loop by an air circulation fan. The air temperature in the return from the pyrolysis drum is around 300°C.

The flue gases pass from the exit of the airheater at around 600°C to the **waste heat boiler**. This is a natural circulation, tail end boiler unit, which generates steam at 400°C and 40 bar, for supply to the turbo-generator. The electricity produced is used to supply the needs of the plant and the excess can be sold.

The boiler has design features intended to minimise high temperature corrosion, and is designed for a high fouling fuel, with a rapping system for on-line cleaning of the tube banks.

The flue gases at the boiler exit are cooled to 170°C in the flue gas cooler, and pass to **Bag Filter No.1**, where entrained fly ash particles are collected. All of the ash material, collected in Bag Filter No.1 and in the boiler hoppers, is recycled to the high temperature combustor, to be recovered as slag. The result is that there are no fly ash discards from the process, which require to be sent for landfill disposal.

Bag Filter No. 2 is fitted with a lime injection system for acid gas emissions abatement. The material collected in Bag Filter No. 2 comprises largely a mixture of unreacted lime, calcium sulphate/sulphite and calcium chloride. This is the only solid discard from the process that is sent for landfill disposal.

The Performance of the Yame Plant

The design MSW quality for the Yame plant is listed in Table 5. It is clear from these data that the waste quality is very different from that of British MSW. It has higher moisture content and lower ash content than the average British MSW, and has lower calorific value. In general terms, it is clear that the MSW delivered to the Yame plant is a lower quality fuel than British MSW.

The overall solid material balance for the Yame plant is presented in Table 6. It is clear from these data that the ash content of the waste actually handled at the plant over the test period had an average ash content less than 10%, as fired, i.e. lower than the design fuel.

The quantity of acid gas clean-up residue produced is dependent on the chlorine content of the MSW. At Yame, the MSW has around 0.2-0.25 % chlorine, as received, and the process generates around 3.5% acid gas clean-up residue, expressed as a percentage by mass of the total MSW throughput. This is the only solid discard material that is sent for landfill disposal. This represents a landfill volume reduction of around 99% of that which would be required for direct landfill disposal of the MSW.

The quantities of ferrous and non-ferrous metals recovered at Yame are modest, however it should be noted that the MSW sent for treatment is the mixed waste residue from a relatively efficient, source separation, recycling scheme. The metals contents of the mixed waste residues from this process are relatively low.

An overall energy balance for the pyrolysis/combustion process and the boiler is presented in Table 7. These data illustrate the stable operation of the process, and melting of all of the ash in the high temperature combustor, without the need for a support fuel. In this case, the Net Calorific Value of the MSW was 7.12 MJ kg^{-1} (as received).

Operational data from the Yame plant has indicated that stable operation of the system without supplementary fuel can be achieved with MSW that has a Net Calorific Value as low as 6.3 MJ kg^{-1} (as received).

The Current Commercial Status of the R21 Process

The R21 technology is one of the leading advanced thermal processes for MSW, worldwide. The process is now fully commercial in the Japanese market, and Mitsui Engineering and Shipbuilding are actively working on the commercialisation of the process in the Far East and in Europe. They have one plant (Yame Seibu) in commercial operation since April 2000.

The second plant at Toyohashi commenced commercial operation in April 2002. Mitsui have orders for four further R21 plants in Japan to be delivered over the next 2-3 years.

2.3.2 The Thermoselect Process

The Thermoselect process has been developed by Thermoselect SA of Locarno in Switzerland. Development started in the late 1980's, and the company operated a demonstration unit (4.2 tonnes h^{-1}) in Fondotoce in Italy from 1992. The first commercial plant was built in Karlsruhe in Germany, which started operation in 1999.

The Thermoselect Process Flow Diagram

The overall process flow diagram is reproduced in Figure 4. The raw MSW is fed to a high pressure, **hydraulic press**, which squeezes out entrained air, increases the bulk density and acts to disperse the fluids within the waste. The solid plug of compressed waste is then fed through the **pyrolysis barrel**, which is indirectly heated using a thermal fluid. As the waste passes through the pyrolysis channel, the water content of the waste is first driven off and then the organic material begins to pyrolyse. The temperature of the waste is increased to around 800°C at the end of the channel, and the pyrolysis of the waste components goes to completion. The total residence time of the waste in the pyrolysis channel is of the order of 1-2 hours.

There are two products of the pyrolysis process, viz:

- The pyrolysis vapour or syngas, which contains steam and the volatile organic components of the waste, and

- The solid residue, which contains char and the majority of the inorganic and metallic components of the waste.

Both of these products are carried forward into the high temperature **gasification reactor**. This is a refractory-lined chamber, into which oxygen is blown. The residence time of the pyrolysis vapour in the gasification reactor is of the order of 2-4 seconds, and the exit temperature from the reactor is around 1200°C. In the presence of oxygen at these temperatures, the product is a synthesis gas comprising principally CO, H_2, CO_2, H_2O and a little nitrogen, with small quantities of HCl, H_2S, NH_3, and HF. The gas also contains fine particles of char and ash carried over from the reactor, and small quantities of vapourised alkali metal and heavy metals salts.

The solid pyrolysis residues are heated to temperatures around 1600-2000°C at the bottom of the gasification reactor, in the presence of injected oxygen and natural gas.

The char is burned off, and the inorganic and metallic components form a molten slag at the base of the reactor. The slag is drawn off continuously into a **water quench system**. The products of this system are:

- Fused ash granules, and
- iron-rich granules, which can be recovered by magnetic separation for recycling.

The hot synthesis gas from the top of the gasification reactor is carried forward to the gas cleaning system. The first process involves cooling in a **water jet quench** section to around 70°C. The rapid quenching of the synthesis gas to low temperatures helps to avoid the formation of dioxins by the 'de-novo' synthesis route. Particulate materials such as char and mineral dusts, which are entrained in the synthesis gas, are also extracted in the water quench section, and returned to the high temperature gasification reactor. The synthesis gas path is connected at this point to a water lock tank, which is intended to act as a safety, pressure relief device. In the event of over-pressurisation of the synthesis gas to above around 500 mbar, the gas pressure is relieved to a safety flare.

Following the water quench section, the cooled synthesis gas enters the **acid gas scrubber** unit, where the HCl and HF are removed. The scrubber liquor is maintained at around pH 3. The volatilised heavy metal species are soluble in the scrubber liquor under these conditions, but the weak acid gas species, such as H_2S, SO_2 and CO_2 do not react significantly with the liquor.

The next stage of synthesis gas cleaning is an **alkaline scrubber** unit, which uses an aqueous sodium hydroxide solution at higher pH to remove residual traces of CO_2 and SO_2.

The synthesis gas then passes through a **desulphurisation stage**, where the scrubbing liquor contains a proprietary Fe III complex

(Sulferox), which removes H_2S from the gas. The H_2S is oxidised within the scrubber to form a suspension of elemental sulphur in water, and the Fe III complex is reduced to a Fe II complex. The elemental sulphur is recovered from the suspension in a centrifuge. Regeneration of the spent Sulferox reagent is achieved by blowing air through the solution in a regeneration tank.

The final stage of the synthesis gas clean-up is a **cold water, gas drying scrubber**, which further reduces the synthesis gas temperature to condense out water and to remove residual traces of the vapourised heavy metals. In some applications, an **activated carbon filter** is installed to act as a final polishing unit for the synthesis gas.

The product of the synthesis gas clean-up train is a clean, dry fuel gas, which can be utilised in a number of further processes, viz:

- for the production of hydrocarbon fuels,
- for the production of hydrogen,
- for the production of industrial chemicals, i.e. methanol and ammonia, and
- for electricity production in gas engines, steam boiler and turbines and in gas turbines.

The process waters generated from condensation of the gasification vapours and from the synthesis gas scrubbing units are treated by conventional pH adjustment and precipitation processes, followed by ion exchange and reverse osmosis techniques. The product sludges can be recycled to the gasifier unit, and in some cases can be valuable products of the process.

Mass Balance and Residue Utilisation/Disposal

The overall mass balance for the Thermoselect process is presented in Table 8. It is clear from the data presented in the table that the process is intended to convert raw MSW to a clean synthesis gas, suitable for further processing, a recyclable metal alloy, a recyclable granular slag and perhaps other recyclable minor products such as sulphur and a mixed heavy metal product.

The recycling of the solid residues from the process depends on the availability of suitable markets for the recycled products. At the Thermoselect plant at Karlsruhe in Germany, customers for all of the solid residues are in place.

The mixed granular product contains both mineral and metallic components, and the composition of this material is presented in Table 9. At the Karlsruhe plant, this material is magnetically separated into two fractions, viz:

- an iron-rich metal fraction, which is sold on as a feedstock to the metals industry, and

- an inert vitreous mineral fraction, which is utilised as a sand blasting agent, as a gravel substitute for concrete manufacture and as a roadbed material.

The mixed salt product from the gas clean-up system comprises principally sodium chloride contaminated with char, carbonate, fluoride and other impurities, and has little economic value.

The mixed metal concentrate from the synthesis gas clean-up system comprises principally zinc, with significant levels of the other heavy metal species, as hydroxides. At Karlsruhe, this material is sold on to the metals recovery industry.

The elemental sulphur generated in the synthesis gas clean-up train is contaminated with char particles and has some heavy metal impurities. At Karlsruhe, this material is sold on to the chemical industry for the manufacture of sulphuric acid.

Energy Balance

As stated above, the Thermoselect process generates a clean synthesis gas, which can be utilised in a number of ways. This is illustrated by examination of the power train arrangements for the industrial-scale plant at Karlsruhe and that proposed for Ansbach.

At Karlsruhe, there is a high demand for heat at all times of the year, and the price of electricity is relatively low. In this application, therefore, the synthesis gas is fired into two boilers, which generate steam for a back-pressure turbine-generator rated at 12 MW_e. The sensible heat content of the synthesis gas quench water and a portion of the steam provide the thermal energy requirement (50 MW_{th}) of the district heating network.

At **Ansbach**, the site requirements are completely different. There is no heat requirement and the power price is attractive. In this case, the system comprises three gas engines, with exhaust gas heat recovery via an Organic Rankine Cycle process. The plant is designed to generate 7.2 MW_e at an estimated cycle efficiency of 38.5%.

These examples illustrate the inherent flexibility of those advanced thermal processes for MSW, which produce a clean synthesis gas, in terms of energy recovery options available.

The Current Commercial Status of the Thermoselect Process

The first commercial plant based on the Thermoselect process was at Karlsruhe in Germany. This plant was commissioned during 1999, however, during 2000 the plant ran into difficulties with environmental regulation authority regarding the emission levels during periods when the plant was flaring gas. The resultant delays and adverse publicity have led to uncertainties about a number of future projects. The second commercial plant in Chiba, Japan, which has been built by Thermoselect's Japanese partner, Kawasaki Steel, has progressed well, and started operation in September 1999. The commercial future for the Thermoselect process in Europe, however, depends to a large extent on the successful resolution of the problems at Karlsruhe, and the establishment of a significant operational record.

2.3.3 The Ebara TwinRec Process

Alstom Power have a license from Ebara Corporation of Japan for the 'twin internally revolving fluidised bed gasifier' and the Meltox process for ash melting, which they are currently marketing in Europe as the TwinRec process. Currently, this technology is being marketed for high calorific value, pre-segregated waste materials such as auto-shredder residues, and plastic and electronic wastes.

To date, there are no reference plants in Europe for this technology, although Ebara has two small plants in Japan, which have been in operation for 3-4 years, and Ebarra has a number of plants on order in Japan.

The Process Flow Diagram for the Ebara Process

The simplified process flow diagram for the TwinRec process is illustrated in Figure 5. The shredded waste material is fed to the **revolving fluidised bed gasification unit**. The design of this unit is based on Ebara's experience with the revolving fluidised bed incinerator for MSW and other wastes, which has been in commercial operation in Japan and elsewhere for some years.

In recent years, Ebara have successfully converted the bubbling fluidised bed combustor to operation in gasification mode.

The fluidised bed gasifier has an inclined air distributor plate with a number of separate windboxes, which supply very carefully controlled air flows under the bed. The air supply system and the furnace/distributor arrangement are designed to promote rapid, turbulent mixing of the fuel within the bed and to induce movement of the large, inert waste components to the sides of the bed for removal through bed drains.

The gasification process is conducted at temperatures in the range 500-600°C, in a silica sand bed. The larger, denser components of the waste (stones, glass and large metallic items, etc.) are rejected through bed drains at the outer walls of the reactor, and report as bottom ash.

After metals recovery, the bottom ash, which represents around 10% or so by weight of the MSW throughput, is sent for landfill disposal.

The product gases, with entrained ash/char particles, pass out from the freeboard region of the furnace, and are carried through hot gas ductwork to the **cyclonic combustion chamber**. The syngas and char are combusted at high temperatures (1350-1450°C). The furnace is operated as a slag tap, with the ash encouraged by the cyclonic action of the air to adhere to the refractory furnace walls and to flow as a molten slag through the slag tap at the furnace bottom.

The hot flue gases from the combustor are then passed to a **conventional waste heat boiler unit**, with steam turbo-generator for power production. The cooled gases are then sent to a **conventional flue gas cleaning system** before exhausting to the atmosphere. The boiler ashes and the solid residues from the flue gas cleaning system are sent for disposal to landfill.

The Current Commercial Status of the Ebara TwinRec Process

The Ebara process has been selected to represent the novel thermal processes for waste that are based on fluidised bed gasification. However, Alstom are not currently marketing the TwinRec process in Europe for the treatment of MSW, but for technical and other reasons have indicated that the technology is more suited to the treatment of higher calorific value wastes of more consistent quality.

This illustrates one of the key difficulties with those technologies that are based on fluidised bed combustion and gasification technologies. The residence time of the waste in the fluidised bed system is relatively short and there is a relatively modest inventory of organic material held within the bed at any one time. The result of this is that fluidised bed systems are relatively vulnerable to any significant variations in the quality of the waste fed to the system. It can be very difficult to maintain stable combustion/gasification conditions in a fluidised bed system, when processing a fuel that is inconsistent in quality.

In general terms, processes based on gasification/pyrolysis on travelling grates or in rotary kilns, where the long residence times in the system can provide some damping of the variations in fuel quality, are preferred for highly variable fuels such as MSW.

For this reason, the Ebara TwinRec process will not be considered further as a novel thermal process for raw MSW in this report.

2.3.4 The Von Roll Recycled Clean Product (RCP) Process

Von Roll Umwelttechnik AG of Zurich, Switzerland has been a major supplier of conventional moving grate incinerator technology for MSW for more than sixty years, and is one of the world leaders in thermal waste processing technology. Von Roll is now part of the Lurgi group of companies.

The RCP process makes use of moving grate technology with an advanced solid residue processing technology, which can be applied both as a retrofit to existing grate-fired incinerators or to new plant.

The Process Flow Diagram for the Von Roll RCP Process

The simplified process flow diagram is reproduced in Figure 6. The waste handling and feeding to the pyrolysis unit are conventional. The first stage of thermal processing is **pyrolysis in a Von Roll forward reciprocating grate**.

The heat requirement for the pyrolysis process is supplied by the partial combustion of the pyrolysis gas with injected oxygen. The pyrolysis temperature on the grate is of the order of 500°C, and the product gas exits the pyrolysis chamber at a temperature of around 900°C. There are two products of the pyrolysis process, viz:

- The pyrolysis gas, and
- The solid residue, containing both the pyrolysis char, and the inorganic and metallic components of the waste.

Both of these products are carried forward to the **smelting reactor**, where more oxygen is injected and the pyrolysis gas is combusted to generate temperatures around 1400°C. At these temperatures, all of the solid materials melt and form a bath of molten slag at the bottom of the reactor. The oxygen is injected tangentially into the furnace to induce a rotatory motion on the top of the slag bath, and hence improve mixing and combustion of the char.

The molten slag is drawn off into the **slag treatment reactor**. The smelting furnace and the slag treatment reactor are based on a technology, which has been patented by Holderbank, and which is known as the **High Temperature Smelt Redox (HSR) process**. This process involves the release of the volatile heavy metals, principally zinc, cadmium and lead into the gas phase. The process gas from the slag treatment unit, containing the volatile heavy metals, is mixed with the gas from the smelting furnace for further processing.

The copper and iron form a fused alloy underneath the alumino-silicate slag, which is periodically tapped off. The residual inorganic slag is pelletised and can be sold on as a constituent of construction materials.

The process gas from the smelting reactor is then combusted in a **circulating fluidised bed furnace** at temperatures less than 1000°C. Oxygen is added to ensure complete incineration of the organic content of the gas. The volatile heavy metal species are oxidised, and condensed. The flue gases from the circulating fluidised bed are then passed through a **conventional waste heat boiler**, which generates steam for the steam turbine or for heating purposes.

The cooled flue gases then enter the **flue gas clean-up system**. This can vary depending on the application, but generally comprises particulate emission control systems and acid gas scrubbing equipment.

The Mass and Energy Balances for the Von Roll RCP Process

The summary mass balance for the Von Roll RCP system is presented in Table 10.

The process uses very large quantities of oxygen in the pyrolysis chamber, the smelting reactor, the HSR slag treatment system and the CFB combustor, and a supplementary fuel oil is required, albeit in relatively modest quantities, in the HSR slag treatment system. Limestone is added to the smelting reactor and the CFB combustor, and there is a make-up sand requirement in the CFB combustor. Activated carbon is injected upstream of the particulate collection equipment, in addition to the other gas cleaning additives and water treatment chemicals. Overall, therefore, the reagent cost element of the operating costs of the Von Roll process is relatively high compared to that of many of the other advanced thermal processes for MSW.

The great majority of the inorganic components of the MSW are converted to a fused slag material, which is suitable for recycling as a component of cements or other construction materials. The copper/iron alloy product is suitable as a secondary resource material for the metals recovery industry. Only around 6-7% by weight of the MSW throughput, principally the water treatment sludges and the solid discards from the gas clean-up train, has to be sent for landfill disposal.

The summary energy balance for the Von Roll RCP process is presented in Table 11. The power export level at around 15%, equivalent to around 400 kWh per tonne of MSW, is relatively low compared to that of other comparable systems. This is due, in the main, to the power requirement of the oxygen plant. It should also be borne in mind that this also includes the energy input from the supplementary fuel.

The Current Commercial Status of the Von Roll RCP Process

The only operating RCP plant is at Bremerhaven in Germany, which is designed to process 6 tonnes h^{-1} of MSW, and was originally commissioned in 1997. The RCP plant is run in parallel with three conventional mass burn incinerators on the Bremerhaven site, sharing MSW reception, storage and feeding systems with the existing plant.

The RCP plant underwent protracted commissioning during 1997-8, and has been operated on a campaign basis rather than continuously. The plant has also undergone significant modification since original commissioning, particularly associated with the smelting chamber and the waste heat boiler unit. The plant has also been employed for the processing of automobile shredder wastes in addition to MSW.

As far as is known, no further projects involving the Von Roll RCP technology for the processing of MSW are planned at the present time, although there has been some recent marketing activity in Japan, involving Hitachi Zosen, who are Von Roll licensees for the RCP technology. Von Roll is currently focussing the future marketing of the RCP technology in Europe on projects involving the treatment of auto-shredder residues and other high calorific value wastes.

For this reason, this process will not be considered further in this report, which is concerned solely with those processes intended for the treatment of MSW.

2.3.5 The Nippon Steel Waste Melting Process

The Nippon Steel process makes use of slag melting and recovery technologies which have been applied in the metallurgical industries for many years, and extends their range of application to the thermal processing of MSW and other mixed wastes. This is one of the few fully commercialised advanced thermal processes for MSW, with a number of plants in commercial operation in Japan since the early 1980's.

The Process Flow Diagram for the Nippon Steel Process

The simplified process flow diagram for the Nippon Steel process is presented in Figure 7. The MSW is first pre-crushed and is then fed to a **large vertical shaft furnace**, along with coke and limestone. The MSW is dried, and then pyrolysed at temperatures up to 1000°C, as it passes down through the shaft furnace. Oxygen is introduced to the bottom of the furnace, and the coke and a portion of the pyrolysis gas are combusted to generate high temperatures for ash melting and to provide heat for the drying and pyrolysis processes. The inorganic and metallic components of the MSW are melted in the bottom of the furnace.

The slag is tapped at a temperature around 1500°C, and then water quenched. The solid product is a granulated slag, which can be magnetically separated into an iron-rich metallic alloy and an inorganic slag granulate.

The excess pyrolysis gas generated in the shaft furnace is carried forward to a high temperature **dust removal process**, and is then burned in air in a **combustion furnace**. The flue gases exit the combustor at a temperature in the range 800-900°C, and pass through the **waste heat boiler**, which generates steam for heating purposes and electricity generation.

The boiler exit flue gas temperature is around 200°C, and the gases are treated in a **conventional gas clean-up system** before exhausting through the chimney.

Ash residues from the combustion chamber and the boiler are moistened, pelletised and recycled to the top of the shaft furnace. Fly ashes and other solid residues of the gas clean-up equipment are treated, and sent for landfill disposal

Mass and Energy Balances for the Nippon Steel Process

The simplified mass balance for the Nippon Steel process is presented in Table 12. It should be noted that the data reflect the quality of the Japanese MSW being processed. This has high moisture content, approaching 50%, as fired, and low ash content, less than 10%, as fired.

The oxygen requirement for the Nippon Steel process is significant, as is the requirement for a supplementary fuel in the form of coke. This will be reflected in both the operating costs of the process and the power export levels.

No energy balance data for the Nippon Steel process are available, however the net power export level is around 400 kWh tonne^{-1} of MSW. This reflects the low calorific value of the Japanese MSW being processed, and the power requirements of the oxygen plant. It should be noted however, that this also includes the energy input from the coke.

The Current Commercial Status of the Nippon Steel Process

The Nippon Steel shaft-type, ash-melting process is a proven technology, with the longest and most extensive reference list and operating history of any of the advanced thermal processes for MSW. Nippon Steel currently has a number of plants under construction, and a number of orders for new plants in Japan.

To date, commercial activity has been solely in Japan, however it is not unreasonable to expect that Nippon Steel will be interested in overseas markets for the technology should these prove to be economically attractive.

2.3.6 The Pyropleq Process

The Pyropleq process was originally developed by PLEQ in the former East Germany in the 1980's. Mannesmann bought PLEQ, and were for some years responsible for the promotion and further development of the pyrolysis process. In recent years, the technology has been acquired by Technip in France.

A small plant, based on the Pyropleq technology for the processing of MSW, industrial solid wastes and sewage sludges has been in operation in Burgau in Germany since 1987.

The Process Flow Diagram for the Pyropleq Process

A simplified process flow diagram for the Pyropleq process has been reproduced in Figure 8.

The feed material for the process at Burgau is a mixture of solid waste materials and sewage sludges, which have been first shredded to a topsize of around 200 mm. The shredded waste is fed through a series of conveyors to the feed chute and the screw feeder to the **pyrolysis reactor**. This is a rotating cylinder, with internal mixing blades, which is indirectly heated, using hot flue gases at around 550°C. The waste materials are first dried, and then pyrolyse as they pass through the reactor over a residence time of 0.5-2 hours. The maximum pyrolysis temperature is of the order of 450-470°C, so the process can be regarded as operating at relatively low temperatures. Lime is added to the reactor for acid gas removal.

The product fuel gas is burned in a downstream **combustion furnace**, after **high temperature particulate collection**. The solid residue from the pyrolysis barrel, containing both char and inorganic/metallic components are quenched with water, and ferrous metals are recovered using an **overhead magnet**, prior to landfill disposal.

The syngas is burned in a combustion furnace at around 1200°C, at 5-8% excess air. The flue gas stream is split into two streams, viz:

- The hot gas, which is used to supply heat to the pyrolysis unit is cooled, using recycled flue gas, to around 600-650°C,

- The balance of the combustion flue gas is remixed with the cold gas returned from the pyrolyser outlet, and the mixed flue gas is delivered to the waste heat boiler inlet.

The **waste heat boiler** generates steam for the **turbo-generator,** or for export as heat. At the boiler exit, the flue gases are controlled by air injection to around 250°C. The **flue gas clean-up system** comprises a fabric filter with activated carbon and sodium bicarbonate injection for particulate and acid gas emission control, and for the abatement of other emissions, including mercury. Flue gas recirculation to the combustion chamber is employed for NO_x emission control.

The dusts collected in the high temperature particulate collection system and in the fabric filter are mixed with the char/inorganic residues from the pyrolysis reactor and the mixed solid residue is sent for landfill disposal.

Overall, the process flow diagram is relatively simple, compared to those of other pyrolysis-based systems.

The system does have the major disadvantage that a difficult, unfused solid residue stream has to be sent for landfill disposal.

The Mass And Energy Balances for the Pyropleq Process

A simplified mass balance for the Pyropleq process is presented in Table 13. The levels of additives, i.e. lime and flue gas clean-up additives are fairly modest. The recovery levels of ferrous metals appear to be very high, at around 12%, for most raw MSW streams in Europe. The main disadvantage of the process compared to a number of the more advanced pyrolysis-based processes is that around 20% by mass of the MSW throughput is generated as a mixture of the pyrolysis solid residue and the fly ash discards, which has to be sent for specially licensed landfill disposal.

The quoted power export level for the Pyropleq process is around 475 kWh per tonne of MSW. This is lower than for conventional MSW incineration systems, but is reasonably good compared to a number of the more advanced processes. This process does not involve ash melting, or the use of oxygen.

The Commercial Status of the Pyropleq Process

The Pyropleq plant at Burgau in Germany, which processes 20,000 tonnes of MSW, 7,000 tonnes of mixed dry wastes and 5,000 tonnes of sewage sludge per annum, through two lines each of 3 tonnes h^{-1}, has been in operation since 1987. The reported availability of this plant is around 7,200 hours per annum, which is not unreasonable for a plant of this type.

A second plant, in Hamm, near Dortmund, is currently under construction. This plant is designed to handle 100,00 tonnes of MSW per annum, through two lines, each of 6.65 tonnes per hour. If the commissioning of the Dortmund plant is completed successfully, the Pyropleq process will have to be regarded as one of the leading pyrolysis-based technologies for the processing of MSW at medium-large scale. It should be noted, however, that the environmental performance of the process, and particularly the handling of the solid residues from the process, is not as attractive as that of some other processes.

The future strategy of Mannesmann/Technip for the commercial development of the Pyropleq process is not known, at the present time. In Britain, the process is currently being marketed by WasteGen UK Ltd.

2.3.7 The Compact Power Process

The Compact Power process has been developed by Compact Power Ltd of Bristol in England since the early 1990's, principally through the operation of a small pilot plant with a capacity of 360 kg h^{-1} of waste, located on a sewage treatment works in England.

A variety of waste materials, including dewatered sewage sludges, MSW, clinical wastes, scraptyre crumb, etc., has been tested. A demonstration plant has been built in Avonmouth, also in England, and this will process up to 8,000 tonnes p.a. of MSW.

The Process Flow Diagram for the Compact Power Process

A simplified process flow diagram for the Compact Power process is presented in Figure 9. The MSW is first shredded to a topsize of 75 mm, and larger ferrous metal items can be extracted by magnetic separation at this stage. The shredded material is then fed to the **pyrolysis unit**. The waste is fed through a series of tubes, which are heated indirectly using hot flue gases from a downstream combustion unit. The maximum pyrolysis temperature is of the order of 800°C, which is relatively high for a waste pyrolysis process, and the residence time of the waste in the pyrolysis unit is of the order of 30 minutes.

The char and inorganic/metal residue from the pyrolysis unit are carried forward to the **fixed bed gasifier**, where the char is reacted with steam and air. The residence time of the solids in the fixed bed reactor is of the order of 30 minutes. The product gas from the gasification unit, principally a mixture of hydrogen and carbon monoxide, with steam, nitrogen and CO_2, is mixed with the pyrolysis gas and carried forward to the **combustion unit**.

In the combustor**,** the pyrolysis gas and the gasifier product gas are burned in air, with fuel oil support, at a temperature of 1250°C, at an excess oxygen level of 8%, and a residence time in excess of 2 seconds.

The flue gas stream from the combustor is split. A portion of the gas is used to supply the heat for the pyrolysis process, and the cooled gas is recycled, mixed with the hot combustion gas and fed to the **waste heat boiler**. The flue gas temperature at the boiler exit is around 200°C. The boiler generates steam, which can be used for heating purposes or can be fed to a turbo-generator for power production.

The **flue gas clean-up system** comprises a dry scrubbing unit with sodium bicarbonate for acid gas emission control, and a Selective Catalytic Reduction (SCR) unit for NO_x emission control.

The Mass And Energy Balances for the Compact Power Process

A simplified mass balance for the process is presented in Table 14. The supplementary fuel requirement for the combustion unit is fairly modest. The major disadvantages of Compact Power technology are associated with the low levels of recyclable materials from the process. Apart from front-end ferrous metal recovery, no material recycling is envisaged. The great majority of the non-combustible material in the MSW is discarded as a bottom ash residue from the gasification unit, and this material has to be sent for landfill disposal.

For the Compact Power process handling MSW with a GCV of 10 $MJkg^{-1}$, the boiler efficiency is quoted as being around 76% and the net power generation efficiency is quoted as being around 20%.

The Current Status of the Compact Power Process

Compact Power has built a small (8,000 tonnes p.a.) plant at Avonmouth to demonstrate the capabilities of the process for the treatment of MSW. This plant has not, as yet, been fully commissioned, and no long term operational data are available. Planning permission has been obtained for a plant in Dumfries in Scotland, designed to process 60,000 tonnes p.a. of non-recyclable municipal, light industrial and commercial waste materials. Compact Power is continuing to pursue a number of projects involving small to medium scale processing of mixed waste materials and MSW. The success of these marketing activities will be largely dependent on the successful demonstration of the long-term operation of the process at the Avonmouth plant.

3. COMPARATIVE ASSESSMENT OF THE TECHNICAL AND ENVIRONMENTAL PERFORMANCE OF THE ADVANCED THERMAL PROCESSES FOR MSW

In Chapter 2 above, brief technical descriptions of conventional waste incineration and of a number of the more advanced thermal processes for MSW are presented. The novel processes were selected on the basis of their commercial status and likely relevance to the British market over the next few years. In this Chapter, an attempt will be made to provide a comparative assessment of the technical and environmental performance of these processes, viz:

- Conventional grate-fired incineration,
- The Mitsui R21 process,
- The Thermoselect process,
- The Nippon Steel Waste Melting process,
- The Pyropleq process, and
- The Compact Power process.

The assessment will be made against the following criteria:

- The overall technical concept,
- The requirement for supplementary fuels or specific reagents, such as oxygen etc., and the energy balance,
- The environmental performance of the process, and
- The overall technical and commercial status of the process.

3.1 Process Comparison

All of the relevant novel thermal processes employ either pyrolysis or gasification of the MSW as the first stage of the thermal treatment or, in the case of the Compact Power process, both. The pyrolysis/gasification is carried out in a rotary drum or a fixed bed reactor. In all of the successful processes, which are capable of handling a poor quality and highly variable feed material such as MSW, the pyrolysis/gasification reactor is large and has a relatively long residence time to provide some damping of the variability of the calorific value and the moisture content of the MSW. One of the key weaknesses of fluidised bed pyrolysis/gasification systems for the processing of highly variable fuels, such as MSW, is the difficulty experienced in the maintenance of stable operating conditions.

The MSW drying and pyrolysis processes are endothermic, and require an external heat source. The Thermoselect, Pyropleq and Compact Power processes all employ hot flue gases from a downstream combustion process, at temperatures in excess of 600°C as the heating medium. The Mitsui R21 employs hot, clean air at around 520°C, in a closed circuit with an internal airheater.

Intrinsically, the use of hot clean air has a number of advantages in that combustion flue gases have a tendency to be corrosive, and there may be problems with ash carryover and deposition on the heat transfer surfaces. The Nippon Steel process involves gasification rather than pyrolysis of the MSW, and the heat requirement is met by partial combustion of the coke, which is added as a supplementary fuel.

The pyrolysis/gasification processes provide two principal products, viz:

- A syngas or pyrolysis vapour, and
- A solid residue, which contains a level of unreacted char material.

The further processing of the syngas/pyrolysis vapour is one of the key differences between processes, viz:

Mitsui R21	direct to high temperature combustion,
Thermoselect	quenched and cleaned,
Nippon Steel	hot gas particulate collection and combustion,
Pyropleq	hot gas particulate collection and combustion, and
Compact Power	direct to high temperature combustion.

The Thermoselect process is clearly very different from the other processes in that the syngas is cleaned, and can be utilised as fuel for a boiler, gas turbine or gas engine.

In the other processes, the pyrolysis/gasification is coupled to a combustor and steam boiler, with or without prior cleaning of the syngas, principally to remove particulate material. Those processes, which involve the use of the combustion flue gas as the external heat source for the pyrolysis stage, require at least some cleaning of the gas to reduce the extent of ash deposition on the heat exchange surfaces within the pyrolysis reactor, although this does not appear to be a feature of the Compact Power process.

The treatment of the solid residues of the pyrolysis process is also a key differentiating factor, viz:

Mitsui R21	metals recovery and char/ash crushing prior to combustion, with ash melting
Thermoselect	ash melting furnace, producing a metal alloy and molten mineral slag,

Nippon Steel	metals recovery and fused mineral slag,
Pyropleq	char/bottom ash and fly ashes sent for landfill disposal, and
Compact Power	char gasification and bottom ash disposal to landfill, with no metals recovery.

The R21, Thermoselect, and Nippon Steel processes involve both the recovery of metals and the production of a fused mineral slag, both of which can be recycled for beneficial use.

The Pyropleq and Compact Power processes generate bottom ashes, from the pyrolysis/gasification reactors, which have to be sent for landfill disposal. This would appear to be a significant disadvantage, both technically and environmentally, of these processes.

As stated previously, the Thermoselect process involves the quenching and cleaning of the syngas prior to utilisation as a fuel for a boiler, gas turbine or gas engine.

All of the other novel processes involve the firing of the product gas with air, and in some cases a support fuel, in a combustion chamber with or without prior cleaning of the gas to remove particulate material. In the case of the Mitsui R21 process, the combustion chamber is operated as a slag tap furnace.

The further processing of the combustion flue gases, for those processes involving combustion, is as follows:

Mitsui R21	high temperature airheater and conventional waste heat boiler,
Nippon Steel	flue gas to conventional waste heat boiler,
Pyropleq	flue gas to pyrolysis reactor and conventional waste heat boiler, and
Compact Power	flue gas to pyrolysis reactor and conventional waste heat boiler.

The Compact Power and Pyropleq processes involve the return of some of the combustion flue gases, controlled to a suitable temperature, to provide the heat for the pyrolysis process. The flue gases contain fine ash particles and significant levels of acid gas species, including HCl. The control of ash deposition, and of corrosion of the heat transfer surfaces in the pyrolysis unit, is a significant technical issue

The R21 process has a high temperature airheater immediately downstream of the combustion chamber, which generates hot clean air for the indirect heating of the pyrolysis unit. The gas temperature at the entry to the airheater is controlled at around 1100°C. The flue gas contains ash carryover from the combustor and significant levels of acid gas species, including HCl. The control of ash deposition and corrosion within the airheater is a significant technical issue.

In all cases, steam is produced in the waste heat boiler at a final steam temperature of around 400°C. This is a relatively modest temperature, but this is conventional for waste incineration to avoid excess metal wastage rates in the superheater section due to high temperature corrosion. In all cases, the steam is used for power generation and/or for the production of heat for process or space heating purposes.

All of the novel processes involve the cleaning of the syngas, in the case of the Thermoselect process, or of the flue gas produced by combustion of the syngas.

In the Thermoselect process, the syngas from the gasification/ash-melting reactor contains fine particulate material (alkali metal salts, vapourised heavy metals and small char/ash particles) and the acid gases (HCl, H_2S and HF). The syngas is quenched with water to temperatures below 70°C, and is then cleaned using conventional gas scrubbing technology.

The solid residues/sludges contain heavy metal salts and other materials, which are sent to landfill disposal. The liquid effluents from the quench and scrubber units are sent to a wastewater treatment plant.

All of the other novel processes involve clean up of the flue gases from a combustor. The details of the emission abatement equipment will clearly depend on the application and the requirements of the appropriate environmental authorisation agency. The general approach to emissions control for particulates and acid gases for the novel processes can be listed as follows:

R21	Two bag filters in series, No.1 for particulate collection and recycling of ashes to the combustor, and No. 2 with dry lime injection for acid gas emission control, with landfill disposal of the solid residues.
Nippon Steel	Conventional flue gas clean-up, with fly ash and solid residues from acid gas scrubbers sent to landfill disposal.
Pyropleq	Conventional flue gas clean-up with a bag filter for fly ash collection with sodium bicarbonate injection for acid gas emission control. The ash and acid gas clean-up solids are mixed and sent for landfill disposal.

Compact Power	Dry scrubber with sodium bicarbonate and Selective Catalytic NOx Reduction (SCR). The solid residues from the dry scrubbing unit are sent for landfill disposal.

It is clear from the information presented above, that all of the novel thermal processes are significantly more complex than conventional mass burn incineration processes, where the raw MSW is combusted on a grate and the hot flue gases pass through a furnace and boiler convective pass. Of the novel processes studied, only the Thermoselect process involves the production of a clean syngas, which can be utilised as fuel for a gas engine or gas turbine. The other processes involve the production of a syngas, which is then combusted in a furnace with heat recovery from the hot flue gas in a steam boiler, i.e. the efficiency of the energy recovery from these processes can be little or no better than that for conventional incineration.

The principal advantages of the novel processes are that they can offer significant improvements in the environmental performance, in terms of the levels of dioxins produced in the system and in the quality of the solid residues and recycled materials from the process. A number of the novel processes produce a fused ash product, which is preferable to the bottom ash and fly ash products from conventional incinerators.

3.2.1 Consumables and Energy Balance

All of the novel thermal processes will require supplementary fuel, steam and power for start up, shutdown and emergency situations. A number of the processes, however, have special consumable requirements during normal operations, viz:

R21	No special requirements. Lime requirement for acid gas emissions control.
Thermoselect	Oxygen and natural gas requirements for the gasification/ash-melting reactor. Syngas cleaning and wastewater treatment reagents required.
Nippon Steel	Oxygen, limestone and coke required for the gasification/ash-melting reactor. Flue gas cleaning reagents required.
Pyropleq	Lime additive required for the pyrolysis reactor. Flue gas cleaning reagent required.
Compact Power	Supplementary fuel requirement for the combustor. Requirements for sodium bicarbonate for the dry scrubber and ammonia for the SCR unit.

Only the Pyropleq and Mitsui R21 processes have no significant special requirements beyond supplementary fuel for start-up and shutdown, and the reagents required for flue gas clean-up and wastewater treatment, and this will be reflected in the operating costs for these processes.

The Thermoselect, Nippon Steel and Compact Power processes all require supplementary fuels, in the form of gas/oil or coke, for the pyrolysis/gasification reactor or the combustor. The Thermoselect and Nippon Steel processes have a further requirement for oxygen for the gasification/ash-melting furnaces. The supplementary fuel and oxygen requirements for these processes will make comparison of the energy balance and power output more complex.

There are considerable difficulties in providing a meaningful and detailed comparison of the energy balance and power output for the different processes, viz:

- A number of the processes have insufficient commercial operating experience with MSW to provide reliable data,
- In some cases, the plants in operation have not been optimised from the point of view of energy recovery and power output, depending on the market conditions under which the plants are operating,
- The data that are available are often based on very different MSW compositional data, with different moisture contents and calorific values,
- A number of the processes have supplementary fuels and oxygen requirements during normal plant operations, and
- A number of the processes incorporate integral ash melting and, in most cases, this has the effect of reducing the power available for export.

The most appropriate benchmark for comparison of the energy recovery performance of the novel thermal treatment processes for MSW is the net power output from conventional waste incinerators. This is dependent both on the quality of the MSW being processed and on the scale of operation.

For British MSW with a GCV of the order of 9 $MJkg^{-1}$, the larger plants, which handle around 300,000-500,000 tonnes of MSW per annum, have a net power output in the range 550-600 kWh per tonne of MSW fired. For the smaller plants, operating in the throughput range 100,000-300,000 tonnes per annum, there are higher levels of heat losses from the boiler and an increased relative parasitic power requirement, and the net power output decreases to around 500-550 kWh per tonne of MSW.

For those processes which produce a fused ash residue material, perhaps the net power output should be compared to that from a conventional incineration plant with an additional ash melting system, i.e. a net power output of the order of 350-400 kWh per tonne of MSW, depending on the ash melting process and the scale of operation.

A comparison of the estimated net power output levels for the selected novel thermal processes is provided in Table 15. It is clear from these data that only the Thermoselect process is capable of net power output levels in excess of those from conventional incinerators. This process is relevant to large-scale operation, and generates a clean syngas for use as a fuel for a gas engine, at relatively high cycle efficiencies, and the net power output also includes the contribution from the supplementary fuel supplied to the gasification/melting furnace.

The processes which produce unfused ash discards from the pyrolysis/gasification processes and a fly ash residue from the flue gas clean-up system, i.e. the Compact Power and the Pyropleq processes have net power output levels around 450-550 kWh per tonne, i.e. broadly similar to those for the smaller conventional incineration plants. The Nippon Steel and the Mitsui R21 processes produce a fused ash and are more comparable in power output to conventional waste incinerators with ash melting furnaces.

3.3 The Environmental Performance of the Novel Thermal Processes

The thermal processing of MSW is a highly regulated process and, amongst other things, specific authorisation to operate is required from the appropriate environmental regulatory authority. For the future market for these processes in Europe, the most relevant document that covers the environmental performance operating standards for this type of plant is:

Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste. Official Journal L 332, 28/12/2000 p. 0091.

In **Article 3**, Definitions, of this document, the definition of waste incineration is as follows:

'Incineration plant' means any stationary or mobile technical unit and equipment dedicated to the thermal treatment of wastes with or without recovery of the combustion heat generated. This includes the incineration by oxidation of waste as well as other thermal treatment processes such as pyrolysis, gasification or plasma processes in so far as the substances resulting from the treatment are subsequently incinerated.'

It is clear that all of the processes discussed in this report fall under this definition, with one possible exception. The Thermoselect process generates a clean syngas, which is exported for use as a fuel in a gas engine or gas turbine. It may be possible to argue that such a process is not an incineration plant and, as such, the environmental performance of such a plant should not be covered under this Directive. For the purposes of this report, however, the Thermoselect process will be treated the same as all the other processes.

The Directive has a number of Articles, which are relevant in the current context, and these will be considered in turn, viz:

- Article 6 Operating conditions
- Article 7 Air emission limit values
- Article 9 residues

Under **Paragraph 1 of Article 6**, the following statement is made:

'Incineration plants shall be operated in order to achieve a level of incineration such that the slag and bottom ashes Total Organic Carbon is less than 3% or their Loss on Ignition is less than 5% of the dry weight of the material. If necessary, appropriate techniques of waste pre-treatment shall be used.'

This Paragraph is intended to provide control over the quality of incineration of the waste, as indicated by the combustible matter content of the solid residues from the process. Clearly, all of the novel processes, which produce a fused ash residue, i.e. the Mitsui R21 process, the Thermoselect process and the Nippon Steel process, will find compliance with this process requirement to be relatively straightforward. Published data from operating plant have indicated that the quality of the fused ashes from these processes is generally very high, with very low unburned carbon levels.

Conventional incinerators without ash melting furnaces will find compliance with this standard more exacting. Grate-fired systems have a relatively short char burn-out time, and the maintenance of sufficiently high temperatures at the back of the grate, at all times, to provide a sufficiently high level of burn-out on the grate may prove to be difficult to achieve for some incineration plants.

For the novel processes which do not produce a fused ash product, i.e. the Pyropleq process and the Compact Power process, this may turn out to be a key compliance issue.

The Pyropleq process produces two solid residue materials, which are sent to landfill disposal, viz:

- An ash/char residue from the pyrolysis reactor, and

- A fly ash material from the ceramic dust filter and a mixed solid residue from the bag filter.

It would appear to be unlikely that the ash/char residue material from the pyrolysis reactor will comply with the requirement for a maximum organic carbon content of 3%, without further treatment.

The Compact Power process produces two solid residue materials, which are sent to landfill disposal, viz:

- A char/ash material from the gasification unit, and
- A fly ash/acid gas scrubber residue from the flue gas clean-up equipment.

The ability of the system, when firing MSW, to provide a gasifier residue that complies with the organic carbon consent limit of 3% for this material, has yet to be demonstrated.

Paragraph 1 of Article 6 also states:

'Incineration plants shall be designed, equipped, built and operated in such a way that the gas resulting from the process is raised, after the last injection of combustion air, in a controlled and homogeneous fashion and even under the most unfavourable conditions, to a temperature of 850°C, as measured near the inner wall or at another representative point of the combustion chamber as authorised by the competent authority, for two seconds.'

This statement, along with the limit on the maximum CO concentration in the flue gases emitted from the plant, is designed to provide control over the quality of the gas phase incineration of the combustion gases. In particular, it is intended to prevent the generation of the precursor compounds of dioxins.

Paragraph 4 of Article 6, permits the authorisation of conditions different form these, under certain circumstances, viz:

'Conditions different from those laid down in Paragraph 1 and, as regards the temperature, Paragraph 3 and specified in the permit for certain categories of waste or for certain thermal processes may be authorised by the competent authority provided the requirements of this Directive are met. Member States may lay down rules governing these authorisations. The change of the operational conditions shall not cause more residues or residues with a higher content of organic pollutants compared to those residues which could be expected under the conditions laid down in Paragraph 1.'

The application of these requirements to a number of the novel thermal processes may prove to be problematic. For instance, it is not clear how the conditions laid down in Paragraph 1 can be applied directly to the Thermoselect process, where the cleaned syngas is used as fuel for a gas engine or gas turbine.

In the Nippon Steel process, the syngas, after dust removal, is burned in a separate combustion reactor. The design of the combustion reactor to ensure compliance with the requirements of Article 6, Paragraph 1 should not present any particular technical problems.

This also applies to the Pyropleq and Compact Power processes, which are similar to the Nippon Steel process in this regard.

In the case of the Mitsui R21 process, the combustion of the syngas and char is carried out in a high temperature cyclone furnace, which is operated as a slag tap, i.e. the flue gas temperatures are in excess of 1300°C, in order to ensue complete fusion of the ash. Compliance with the requirements of Article 6, Paragraph 1 would not appear to represent a particular problem. One of the key advantages of this process is the very low dioxin generation, as demonstrated in the commercial plant at Yame.

Article 7 of the Directive is concerned with the limit values for the emissions to air. The Air Emission Limit Values are presented in Annex V of the Directive, and a number of the most important requirements are reproduced in Table 16 (a) and (b).

The Air Emission Limit Values, prescribed in Directive 2000/76/EC represent a significant change to those already in force in Britain for MSW incinerators.

It is envisaged, however, that all of the conventional and novel thermal processes for MSW, considered in this report, will be able to comply with these requirements, if fitted with the necessary flue gas cleaning equipment.

Article 9 of Directive 2000/76/EC is concerned with the solid residues resulting from the incineration of wastes, and contains the following statement:

Residues resulting from the operation of the incineration or co-incineration plant shall be minimised in their amount and harmfulness. Residues shall be recycled, where appropriate, directly in the plant or outside in accordance with relevant Community legislation.

This is a very general statement, however it would appear that those processes that involve the recycling of ferrous and non-ferrous metals from the MSW would be preferred. Those processes that involve the production of a fused slag material, rather than bottom ash and fly ash residues, would have significant advantages, both in terms of the volume of solid residues generated and of the quality of the residues produced.

In this context, it is relevant to discuss the issue of the release of dioxins and furans from thermal processes for MSW. The current legislation in Britain, IPC Guidance Note S2 5.01: Waste Incineration, and Directive 2000/76/EC are concerned only with the control of the emissions of dioxins and furans to air. There are no specific requirements to control the releases of these species to land or water, or to limit the total releases to all media. It is widely recognised that the great majority of the total releases of dioxins and furans from MSW incineration and thermal processing plants are in solid form, i.e. adsorbed to the surfaces of fly ash particles and of the fine particulate material discards from the flue gas cleaning equipment.

It would appear, therefore, that those processes which do not generate fly ash residues, and which can demonstrate the lowest total releases of dioxins and furans to all media, can claim significant advantages with respect to their ability to comply with the requirements of Article 9 of Directive 2000/76/EC, viz:

Mitsui R21	No fly ash or bottom ash generated. All ash materials converted to a fused slag. High efficiency and high quality metals recovery.
Thermoselect	No fly ash or bottom ash generated. Fused metal/mineral granulate produced. Sulphur recovery.
Nippon Steel	Granulated slag. Ferrous metal recovery. Fly ash residue from flue gas cleaning system.
Pyropleq	Metals recovery. Both pyrolysis char/bottom ash and fly ash produced.
Compact Power	No metal recovery. Both pyrolysis/gasification bottom ash and combustion fly ash produced.

It is clear from this comparison that the Pyropleq and the Compact Power processes score poorly in terms of the quality of the solid residues, and the quantity of material that has to be sent for landfill disposal. The Mitsui R21 and the Thermoselect processes score particularly well in this regard.

This is also the case for conventional combustion-based incineration technologies. In most cases, both a furnace bottom ash and a fly ash from the boiler hoppers and the flue gas cleaning equipment are produced, and both of these materials are commonly sent for landfill disposal. It is also the case that the ferrous metals recovered from most of the conventional incinerators is of relatively poor quality and that the efficiency of metals recovery from incinerator bottom ashes is not very high. The relatively high temperatures and the oxidising conditions that apply in incinerator furnaces, result in the recovered ferrous metal being in a partially oxidised and relatively dirty state.

In terms of the quantity and quality of the solid residues, and the ability to demonstrate compliance with the requirements of Article 9 of Directive 200/76/EC, conventional incineration technologies do not score particularly well. This represents one of the key areas where a number of the novel thermal processing technologies can demonstrate improved performance over the conventional incineration technologies.

3.4 The Overall Technical Status of the Processes

In this context, it should be clearly stated at the outset that only conventional grate-fired, or in one case, fluidised bed-fired incineration systems are currently in operation in Britain for the treatment of MSW. In this respect, therefore, conventional, combustion-based incineration must be regarded as being the established technology, the benchmark against which all other technologies must be compared.

Two of the novel technologies considered can be regarded as being fully commercially demonstrated in the Japanese market, viz:

Nippon Steel	There nine plants processing MSW, which are currently in operation, and a number of new plants ordered.
Mitsui R21	There are two plants currently in commercial operation, a second plant being commissioned and a number of new plants under construction.

It should be noted, however, that the Japanese market has a number of important differences from the markets in Britain and in continental Europe, viz:

- For cultural and other reasons, the MSW is very different from that in most European countries. In general terms, it has higher moisture content and lower calorific value, but has much lower ash content.

- The emphasis in Japan is increasingly on the stabilisation of wastes and on the recovery and recycling of useful materials. There is a very strong emphasis on the control of the total release of dioxins and furans to all media, and on the reduction of the volumes of the waste that is sent for landfill disposal. Processes that generate a fused ash residue are regarded very favourably.

- There is much less emphasis on the recovery and export of energy from waste processing plants. Many plants are not licensed to export either power or heat.

- The commercial situation in Japan is somewhat different from that in Europe. The capital costs of these processes are relatively high, and this may represent a barrier to their wider adoption in the world market.

The scope for the commercialisation of the Nippon Steel process in Europe may be limited. It is known, however, that Mitsui are currently involved in promotional activity in Britain and Europe, through their subsidiary company Mitsui Babcock. This activity includes a cost reduction exercise to improve the commercial competitiveness of the R21 process in world markets.

The **Pyropleq** process can be regarded as being one of the more commercially proven technologies, with more than ten years operating experience at the plant at Burgau in Germany. This plant is modest in size, handling around 30,000 tonnes per annum of a variety of solid waste materials, through two lines of around 3 tonnes per hour capacity. The mixed waste materials include:

- Municipal solid waste and bulky wastes,

- Industrial and commercial wastes, and

- Sewage sludge.

A further plant at Dortmund in Germany is under construction. This plant will handle a mixture of high calorific value solid waste materials, including MSW, plastic waste, dried paper sludges and industrial wastes. The Dortmund plant is designed to handle 100,000 tonnes p.a. with two streams of around 6.5 tonnes per hour capacity.

The future marketing strategy for the Pyropleq process elsewhere in Europe is not known at present, and the future prospects for this technology will be strongly dependent on the performance of the new plant in Dortmund. The Pyropleq technology is currently being marketed in Britain by WasteGen UK Ltd.

The future commercial development of the **Thermoselect** process is also open to some uncertainty. At the present time, the process must be regarded as being only semi-commercial, in that the performance of the process has not, as yet, been demonstrated at the plant in Karlsruhe in Germany, or at the plant in Chiba in Japan built by Thermoselect's Japanese partner Kawasaki Steel. The Karlsruhe plant has had lengthy problems with the commissioning and the achievement of a level of performance necessary to satisfy the regulatory authorities. The Chiba plant is operated with the local Kawasaki factory, providing cleaned syngas as a feedstock. The successful operation of the Karlsruhe plant over a prolonged period, and with high availability, is required before the process can be regarded as being fully commercial.

The **Compact Power** process is the least developed of the novel thermal processes considered in this report. The company have built a small (8,000 tpa) demonstration unit at Avonmouth, near Bristol in England. This plant is currently undergoing short-term trial work processing MSW, in support of the company's commercial activities in Britain and elsewhere. This has required significant modification of the process, as tested at the pilot unit in Finham, England.

At the present time, no long-term performance data from the Avonmouth plant are available, and until such a time as this plant has been in operation over a prolonged period with good availability, the process must be considered as being only in the demonstration phase.

Compact Power has recently been granted planning approval for a plant at Dargaval, near Dumfries, in Scotland. The plant is intended to process 60,000 tonnes per annum of mixed waste materials, including non-recyclable municipal waste, light industrial and commercial wastes, timber, textiles, rubber tyre shred and sewage screenings, and would generate 7.8 MW_e. This would be the first advanced thermal processing plant operating commercially in Britain and, if built and operated successfully, would represent a major step forward for the Compact Power process.

4. ECONOMIC ASSESSMENT OF THE ADVANCED THERMAL PROCESSES FOR MSW

The current trend in the financing of waste management activities in Britain is towards the encouragement of the private sector to make the capital investment in new facilities. In this context, the likelihood is that the funding of waste management activities will be through project financing, where the funds for the construction and operation of a project will be secured only on the value of the project assets and on the value of future revenue streams. Commonly, the investment will be made by a special purpose, limited company, which will hold the project assets, viz:

- The project-funded asset, e.g. the energy from waste facility, and
- A series of contracts, which will deal with the construction, operation and maintenance, and the trading arrangements (waste supply, power sales etc.), associated with the activities of the special purpose company.

The special purpose company can be financed entirely out of equity, however, it is more common for project finance to be made up from a combination of equity and debt. At the present time, waste management projects in Britain are being financed, in the main, by a combination of equity and debt on the private side, and PFI credits (government subsidy) on the public side. The project assets are owned by the private sector, and the contract with the public sector for waste management is in the form of a contract for services, based on a gate fee per tonne of waste handled. The gate fee represents one of the major income streams to the project.

In this context, the economic comparison between conventional waste incineration plants and the more novel thermal processes for MSW must be made on the basis of two parameters, viz:

- The total investment, which includes both the capital costs of the plant and the project development costs, and
- The gate fee, which takes into account both the costs of finance, and the overall operating costs and incomes through the working life of the plant.

In this section of the report, an attempt is made to perform such an economic comparison, although it should be noted that different organisations have very different methodologies for the preparation of cost estimates, and this can make direct comparisons very difficult.

In the case of the more novel technologies, the capital and operating costs can only be very crude estimates, since no plants based on these technologies have been built in Britain to date, and only a few of the novel technologies can be regarded as being fully commercial anywhere in the world. The availability of reliable cost data for these technologies is very limited. In this context, it should be noted that a number of the companies involved in the development and marketing of the new technologies have been providing estimates of the capital and operating costs of specific processes. These estimates have not, as yet, been tested commercially, and may prove to be over-optimistic.

It is also relevant in this context to consider the impact of the Renewables Obligation Order 2002 on the economics of energy from waste projects in Britain.

The Renewables Obligation is a Statutory Instrument, which was introduced by the British government on the 1st of April 2002 to encourage the generation of electricity from renewable sources in England and Wales. Similar orders for Scotland and Northern Ireland also apply.

The order places an obligation on the suppliers of electricity to obtain an increasing proportion of the electricity supplied from renewable sources, allowing suppliers to buy out of the obligation at an enhanced price. This effectively provides a subsidy to the generators of electricity from renewable sources, and the intention is to create a market in Renewable Energy Certificates (ROC's) in Britain.

This is of direct interest to the waste management industry, since the government have decided that thermal processing plant for MSW, which are based on advanced processes, involving the pyrolysis or gasification of MSW, will be eligible, and can command an enhanced price for a portion of the electricity generated. Only that portion of the electricity that is generated from the MSW, which comes from the non-fossil, ie non-plastic, material in the MSW will be eligible. To a first approximation, this is of the order of 50% of the power generated in an energy from waste plant.

The precise value of the Renewables Obligation Certificates is not easy to predict, however it is clear that this will have a significant impact on the economics of the advanced thermal processes, and provide a significant advantage over conventional mass burn incineration, which will not be eligible under the Renewables Obligation.

4.1 The Capital Costs of Waste to Energy Plants

The current capital and total investment costs for conventional mass burn incineration plants in Britain are reasonably well understood. A number of plants of different sizes have been built over the past ten years or so, and the declared capital costs of these plants provides a reasonable basis on which to estimate the capital costs of future plants.

A breakdown of the total investment costs for mass burn incineration/energy-from-waste projects at three scales of operation, i.e. 70,000, 200,000 and 400,000 tonnes per annum of MSW are presented in Table 17. In the development of these costs, the assumption is made that the supply of the plant and equipment is through a turnkey contract, i.e. the risks associated with the plant construction, with the technology and with plant performance, at least during the warranty periods, are borne by the turnkey contractor. These risks are obviously reflected in the turnkey contract price.

It should be noted that the turnkey contract for plant and equipment is the largest single element of the total project finance requirement, and is probably the cost item that can be estimated with most confidence.

The costs of land purchase, of the civil engineering elements of the project and of the electrical connection to the grid are all significant, and are highly site specific. In this case only generalised cost estimates can be given. In addition to this, it is also clear that the development costs for energy from waste projects are relatively high and are subject to a significant degree of variability because of the difficulties in obtaining planning permission and other consents for this type of project.

It is apparent from the data presented in Table 17 that there are significant economies of scale for conventional mass burn incineration projects over the range 70,000-400,000 tonnes p.a. The total funds required can vary from values less than £200 per tonne per annum of MSW to more than £350, over this range of scales of operation.

A general breakdown of the cost elements of the turnkey project into individual plant and equipment packages is presented in Table 18. Clearly, the incinerator and boiler package, the turbo-generator package and the flue gas cleaning equipment package are the largest cost items. The costs of the flue gas cleaning equipment for future projects must be subject to a degree of uncertainty due to the impact of the new EC Incineration Directive on the environmental performance requirements for energy from waste plants.

4.2 The Operating Costs, Incomes and Gate Fees for Conventional Mass Burn Incineration Plants

Estimates of the annual operating costs of conventional, mass burn incineration plants at three scales of operation are listed in Table 19. The major items of operating cost include the disposal costs for the solid residues from the plant, i.e. the bottom ash/fly ash/APC discards and the waste water treatment sludges, and for labour, maintenance and consumables, with the allocations for insurances, management fees etc. making a relatively modest contribution. The labour and maintenance costs are reasonable easy to estimate based on current plant experience. The costs of residue disposal are rising in a less predictable fashion, and may be subject to significant step changes over the lifetime of a new incineration project in response to future legislative changes and Landfill Tax increases.

The levels of power production and export from modern, mass burn incineration plants, and the plant availability levels are reasonably well understood, as are the production rates and sales incomes from recycled metals. It is possible, therefore to prepare reasonable estimates of the non-gate fee incomes to the project.

The estimates of the capital and annual operating costs, and of the incomes from the sales of power and recycled materials from the plant, have been used as input to a commercial business model for projects of this type.

The model includes what are considered to be reasonable financial assumptions, and has been set up to provide reasonable project and equity returns. In this way, estimates of the required gate fee per tonne of MSW at current values have been made. The estimated gate fees for the three scales of operation are also listed on Table 19.

The effect of the plant throughput on the required gate fees is clear. The relationships between the plant throughput and both the investment costs and the annual operating costs are non-linear, and the effect is to increase the gate fee relatively sharply from around £30 per tonne to £83 per tonne, with decreasing plant throughput, over the range 400,000 to 70,000 tonnes p.a. It should be noted that the estimated gate fees at the lower end of the size range are more than twice the current gate fees for the landfill disposal of MSW in Britain. This will represent a significant commercial disincentive for the construction of conventional waste incinerators at lower throughputs in spite of the fact that smaller units are preferred for public perception, planning and other reasons. This is one of the issues that will need to be resolved within the waste management industry in Britain over the next ten years or so.

4.3 The Capital And Operating Costs of the R21 System and the Other Novel Thermal Processes for MSW

It is very difficult to provide simple comparisons of the estimates of the capital and operating costs for the novel thermal processes for MSW, relevant to the British market. By their very nature, these processes are new to the market on a worldwide basis, and no plants have been built in Britain to date. For this reason, no authoritative estimates of the costs of these processes can be provided with any confidence.

The best and most up-to-date information available is in the Juniper Reports, and the authors are very careful to spell out the early stage of development of most of the relevant processes and the difficulties of providing meaningful cost comparisons.

The capital cost estimates presented as £ per tonne of MSW per annum for both mass burn incineration and a number of the novel processes are listed on Table 20. It is clear from the data presented in this table that relatively wide ranges of costs are quoted for individual processes, to reflect the variability of specific project requirements and site-specific cost items.

The estimated capital costs for the different processes also vary widely, reflecting their degree of complexity. The most expensive technology by some way is the Thermoselect process. Those technologies that produce a fused slag residue, such as the Thermoselect process and the Von Roll RCP process, tend to be significantly more complex and more expensive than the technologies, such as the Pyropleq and the Compact Power processes, which produce fly ash and bottom ash discard materials. Current estimates for the Mitsui R21 process indicate that the capital costs for this technology will lie somewhere between those for mass burn incineration and the Thermoselect process, at a throughput of around 70,000 tonnes per annum, depending on the specific project requirements.

The estimation of the operating costs of the novel thermal processes is even more difficult. The authors of the Juniper Report, which provides the most comprehensive review of the novel thermal processes for waste and biomass materials, are of the view that it is meaningless to attempt to provide generalised estimates of the operating costs of the novel processes. It is likely, however, that the labour and administration/site establishment costs are likely to be reasonably similar for plants of similar throughput, irrespective of the technology employed. The plant maintenance costs will vary between technologies, but are likely to reflect the level of process complexity, and hence the process capital costs.

The Juniper report does provide, however, a listing of the items of consumable costs, which may help to distinguish between processes in a general sense. For instance, both the Thermoselect and Von Roll processes have a significant requirement for oxygen, of the order of 500-800 kg tonne^{-1} of MSW, and both require supplementary fuel. The cost, particularly of oxygen, can vary markedly from site to site. The Compact Power and Pyropleq processes both generate significant quantities of fly ash and bottom ash residues, and the costs of disposal of these materials are significant. The costs of disposal of the solid discard materials to landfill vary widely from site to site, and have been increasing significantly over the past few years. In these cases, the costs of residue disposal will be a very significant and increasing element of the annual operating costs of plant.

The Mitsui R21 process has a number of significant advantages in this regard in that the process has no requirements for supplementary fuel or oxygen under normal operating conditions, and only relatively small quantities of solid discards from the process require landfill disposal.

5. CONCLUSIONS

In this report, an attempt has been made to provide a description, and technical and economic assessments, of the novel thermal processes for the treatment of MSW, which are relevant to the emerging British market. This is not an easy task in that the majority of the relevant processes are under development or at best in the demonstration phase. Only a relatively small number of the relevant technologies can be regarded as being in full commercial operation any where in the world, and none are in commercial operation in Britain.

Brief technical descriptions of seven novel processes are given in this report, and five technologies have been selected for more detailed comparison, on the basis of their development status and likely relevance to the emerging British market, viz:

- The Mitsui R21 technology,
- The Thermoselect process,
- The Nippon Steel Waste Melting process,
- The Pyropleq process, and

- The Compact Power process.

All of these technologies are based on pyrolysis and/or gasification of the MSW or shredded MSW as the initial element of the thermal treatment. In the case of the Thermoselect process, a cleaned syngas, suitable for use as a fuel for a gas turbine, a gas engine or a boiler is the primary product. In all other cases, the pyrolysis/gasification process is coupled with a combustor with energy recovery in a steam boiler.

Three of the processes, i.e. the Mitsui R21 process, the Thermoselect process and the Nippon Steel process provide a fused ash product, which is suitable for recycling. The Pyropleq and Compact Power processes produce bottom ash and fly ash discard streams, which are sent for landfill disposal after suitable treatment.

The technical comparison of the candidate processes has been made under the following subject areas:

- The overall technical concept,
- The energy balance and the requirement for supplementary fuels or specific reagents,
- The environmental performance in the context of the requirements of the new EC Directive on the incineration of waste, and
- The overall technical and commercial status of the technologies.

In general terms, those processes which do not require oxygen or a supplementary fuel under normal operating conditions, and which provide a fused ash product are preferred technically, and the environmental performance of these processes represents a step change improvement over conventional mass burn incineration and over some of the other novel technologies. These technologies, however, tend, to be more complex, have lower net power export efficiencies and higher capital costs than the other processes.

The provision of a meaningful comparison of the economics of the novel processes is a very difficult task, in that none of the relevant processes is in commercial operation in the British market, and this means that the availability of authoritative comparative cost information is limited.

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Reference was also made to a number of websites, too numerous to list.

Plant	**MSW throughput (ktonne p.a.)**	**Net electrical generation capacity (MW_e)**
Cleveland	245	20
SELCHP (London)	420	32
Tyseley (Birmingham)	350	32
Isle of Wight (RDF plant)	15	1.8
Dundee	120	14
Lerwick	26	No power output
Coventry	220	17.7
Dudley	90	7
Wolverhampton	105	8
Edmonton (North London)	600	32
Stoke	200	12.5
Nottingham	150	13
Bolton	130	10
Pebsham (RDF plant)	75	2.5

Table 1 **The MSW incineration plants currently in operation in Britain (after the Energy from Waste Association, Dec. 2000)**

Constituent	**Unit**	**Low Calorific Value MSW**	**Average Calorific Value MSW**	**High Calorific Value MSW**
Category Assay				
Paper	% w/w	26.0	30.7	35.0
Plastic film	% w/w	3.0	4.6	5.0
Dense plastics	% w/w	2.0	3.4	4.0
Textiles	% w/w	4.0	3.3	5.0
Misc. combustibles	% w/w	6.0	5.2	8.0
Glass	% w/w	7.0	7.9	10.0
Putrescibles	% w/w	20.0	22.5	12.0
Ferrous metal	% w/w	6.0	7.5	9.0
Non-ferrous metal	% w/w	1.0	1.2	2.0
Fines, less than 10 mm	% w/w	19.0	11.1	8.0
Totals	% w/w	94.0	97.4	98.0

TABLE 2 Category assay data for British MSW (after Patel and Higham, 1995)

Constituent	Units	Low Calorific Value MSW	Average Calorific Value MSW	High Calorific Value MSW
Proximate Analysis				
Moisture	% w/w	32.7	31.4	26.1
Ash	% w/w	30.3	27.8	30.5
Volatile Matter	% w/w	33.3	36.8	39.5
Fixed Carbon	% w/w	3.9	4.1	4.2
Ultimate Analysis				
Moisture + Ash	% w/w	63.0	59.2	56.6
C	% w/w	19.8	22.1	23.7
H	% w/w	2.8	3.2	3.4
N	% w/w	0.7	0.6	0.6
O (by diff.)	% w/w	13.2	14.2	15.0
S	% w/w	0.1	0.1	0.1
Cl	% w/w	0.4	0.6	0.6
Heavy metals				
Pb	ppm	133	133	114
Cd	ppm	19	21	25
Hg	ppm	0.3	0.3	0.3
Gross Calorific Value	MJ kg^{-1}	8.30	9.39	10.10

TABLE 3 Proximate, Ultimate and Heavy Metal Analysis and Gross Calorific Value for British MSW (after Patel and Higham, 1995)

Plant item	Description
Waste reception	Waste pit, and crane with a 4.3 tonnes capacity bucket
Waste crusher	Biaxial shear shredder, hydraulic, 90 kW
Pyrolysis unit	Rotary kiln, 3.1 m diameter, 25.3 m in length, indirectly heated with hot air.
Combustion furnace	Vertical, tangential firing, refractory-lined, operated as a slag tap furnace.
High temperature airheater	Suspension panel arrangement
Waste heat boiler	Natural circulation, final steam at 400°C and 40 bar.
Flue gas clean-up	Fabric filter for particulates, followed by lime injection and second fabric filter
Pyrolysis solids processing	Vibratory screen, ferrous metal and aluminium recovery
Acid gas clean-up residue treatment	Chemical treatment and cement encapsulation

Table 4 Listing of major plant components for the R21 process.

Parameter	**Reference waste**	**Low quality waste**	**High quality waste**
Moisture (%, as received)	50	55	43
Combustibles (%, as received)	36	30	43
Sulphur (%, as received)	0.04	0.04	0.04
Chlorine (%, as received)	0.21	0.21	0.21
Ash (%, as received)	14	15	14
Net Calorific Value (MJ kg^{-1}, as received)	6.7	4.2	10.0

Table 5 Design MSW quality for the R21 plant at Yame in Japan.

Material	**Quantity (tonnes)**	**Percentage of MSW throughput**
MSW	20,477	100
Slag	1,568	7.66
Acid gas clean-up residue	728	3.56
Ferrous metal recovered	80	0.39
Non-ferrous metal recovered	32	0.15

Table 6 Overall solid material balance for the R21 plant at Yame.
(21 Dec. 1999 – 31 July 2000)

HEAT INPUT			**HEAT OUTPUT**		
Item	**MJ h^{-1}**	**%**	**Item**	**MJ h^{-1}**	**%**
MSW input	31,475	100.00	**Flue gas losses**	3,098.9	9.85
Boiler feedwater	5,160	16.39	**Circulating flue gas**	902.5	2.87
Circulating flue gas	662.6	2.11	**Flyash**	62.4	0.20
Circulating ash	16.7	0.05	**Recovered steam**	27,826.0	88.40
Cooling water	597.8	1.90	**Continuous blowdown**	78.7	0.25
Combustion air	45.2	0.14	**Slag**	359.6	1.14
Slag tap heating burner	272.1	0.86	**Ferrous and non-ferrous metals**	1.3	0.00
			Cooling water	1,095.9	3.48
			Heat losses	2862.8	9.09
			Hot air losses	1,941.9	6.17
Totals	**38,229.9**	**121.45**	**Totals**	**38,229.9**	**121.45**

Table 7 The overall energy balance for the R21 plant at Yame.

INPUTS (for MSW with a GCV of 10 MJ kg^{-1})	**kg $tonne^{-1}$ of MSW**
Oxygen	514
Natural gas	23.3
Additives (gas cleaning)	8.9
Additives (water treatment)	11.1
RECYCLABLE OUTPUTS	
Metals	29
Vitrified mineral product	230
Sulphur	2
Clean synthesis gas	895
RESIDUES	
Heavy metal sludge and salts	19.5

Table 8 Mass balance for the Thermoselect process (after Juniper 2000)

Component/property	Unit	Value
Water content	%, w/w	5-10
Bulk density	kg m^{-3}	1,400 approx.
Loss on ignition	% w/w	0.1
Silicon	% w/w	24.5
Aluminium	% w/w	3.4
Calcium	% w/w	8.9
Iron	% w/w	9.3
Cadmium	mg kg^{-1}	< 6.0
Mercury	mg kg^{-1}	< 2.6
Antimony	mg kg^{-1}	18
Arsenic	mg kg^{-1}	< 3.7
Lead	mg kg^{-1}	202
Chromium (total)	mg kg^{-1}	2,670
Copper	mg kg^{-1}	2,240
Manganese	mg kg^{-1}	1,470
Nickel	mg kg^{-1}	265
Tin	mg kg^{-1}	93
Zinc	mg kg^{-1}	890

Table 9 Analysis data for the granular mineral product of the Thermoselect process (after Mucha and Stahlberg, 2001)

INPUTS (for MSW with a GCV = 10.5 MJ kg^{-1})	kg $tonne^{-1}$ of MSW
Oxygen	**790**
Limestone	**4**
Fuel oil	**5**
Additives (gas cleaning)	**6**
Graphite/activated carbon	**4**
Sand	**10**
RECYCLABLE OUTPUTS	
Slag	**205**
Copper/iron alloy	**6**
RESIDUES TO LANDFILL	
Heavy metal sludge	**18**
Other solid residues	**48**

Table 10 Mass balance for the Von Roll RCP process (Juniper, 2001)

Component	Fraction of total energy input (%)
Condensed waste heat	54
Heat losses	15
Generator losses	2
Parasitic electricity consumption	6
Electricity usage in O2 plant	8
Power export	15

Table 11 Summary energy balance for the Von Roll RCP Process (Juniper, 2001)

INPUTS (for MSW with a GCV of 8.5 MJ kg^{-1})	**kg tonne^{-1} of MSW**
Oxygen	**Not specified**
Limestone	**50**
Coke	**40-50**
RECYCLABLE OUTPUTS	
Granulated slag	**90**
Iron-rich alloy	**10**
RESIDUES TO LANDFILL	
Fly ashes	**30**

Table 12 The simplified mass balance for the Nippon Steel process (after Juniper, 2001)

INPUTS (for MSW with a GCV of 10 MJ kg^{-1})	**kg tonne^{-1} of MSW**
Lime	15-20
Sodium bicarbonate and carbon	26
RECYCLABLE OUTPUTS	
Ferrous metal	120
RESIDUES TO LANDFILL	
Solid discards from the pyrolysis process	180
Fly ash residues	30

Table 13 Simplified mass balance for the Pyropleq process (Juniper 2001)

INPUTS (for MSW with a GCV of 10 MJ kg^{-1})	**kg tonne^{-1} of MSW**
Supplementary fuel	1.8
Sodium bicarbonate	11
Activated carbon	Not specified
RECYCLABLES	
Ferrous metals	Not specified
OUTPUTS	
Bottom ashes	260
Flue gas cleaning residues	14

Table 14 **A simplified mass balance for the Compact Power process**

Process	**Net electrical power output (kWh per tonne of MSW**
Conventional incinerator (>300,000tonnes p.a.)	550-600
Conventional incinerator (<300,000 tonnes p.a.)	500-550
Conventional incinerator with ash melting	350-400
Mitsui R21	300-450
Thermoselect	650-700
Nippon Steel	400
Pyropleq	450-500
Compact Power	550

Table 15 **A comparison of the net power output from the relevant thermal processes for MSW**

Species	Maximum allowable concentration
Total dust **(Daily average)**	10 mg Nm^{-3}, dry, at 11% O_2
Gaseous and vaporous organic substances, expressed as total organic carbon. **(Daily average)**	10 mg Nm^{-3}, dry, at 11% O_2
Hydrogen chloride (HCl) **(Daily average)**	10 mg Nm^{-3}, dry, at 11% O_2
Hydrogen fluoride (HF) **(Daily average)**	1 mg Nm^{-3}, dry, at 11% O_2
Sulphur dioxide (SO_2) **(daily average)**	50 mg Nm^{-3}, dry, at 11%O_2
Nitrogen monoxide (NO) and nitrogen dioxide (NO_2) expressed as nitrogen dioxide for existing incineration plants with a nominal capacity of 6 tonnes per hour or new incineration plants **(Daily average)**	200 mg Nm^{-3}, dry, at 11% O_2
Carbon monoxide **(Daily average)**	50 mg Nm^{-3}, dry, at 11%O_2
Dioxins and furans **(Average values over a 6-8 hour period)**	0.1 ng TEQ Nm^{-3}, dry, at 11% O_2
Cadmium + Thallium and their compounds.	Total 0.05 mg Nm^{-3}, dry, at 11% O_2
Mercury and its compounds, expressed as Hg	0.05 mg Nm^{-3}, dry, at 12% O_2
Antimony + arsenic + lead + Chromium + cobalt + Copper + manganese + nickel + vanadium and their compounds, expressed as the metal.	Total 0.5 mg Nm^{-3}, dry, at 11 % O_2

Table 16 Air emission limit values – EC Directive 2000/76/EC on the Incineration of Waste – Annex V (a), (d) and (e).

Cost item	70,000 (tonnes p.a.)	200,000 (tonnes p.a.)	400,000 (tonnes p.a.)
Land purchase (£ million)	0.3	0.6	1.0
Buildings and civil engineering (£ million)	6.1	10.2	15.7
Turnkey contract for plant and equipment (£ million)	18.1	30.5	47.3
Electrical connection (£ million)	0.5	0.7	1.0
Total Capital expenditure (£ million)	**25.0**	**42.0**	**65.0**
Project development costs (£ million)	0.6	1.0	1.5
Financing costs (£ million)	0.3	0.5	0.8
Capitalised interest during construction (£ million)	3.1	5.3	8.0
Loan fees (£ million)	0.9	1.5	2.2
Total funds required (£ million)	**29.9**	**50.2**	**77.5**

Table 17 Capital costs of conventional energy from waste plants based on mass burn incineration

Cost items	% of the turnkey contract cost
Waste reception	2.5
Incinerator, boiler and auxiliaries	39.2
Bottom ash system	0.9
Fly ash system	3.6
Steam turbine and auxiliaries	17.8
Flue gas cleaning	10.0
Chimney	1.7
Utilities	3.7
Electrics	6.6
Instrumentation	5.7
Miscellaneous equipment	0.4
Mechanical installation	1.4
E&I installation	3.8
Site establishment	2.7

Table 18 Percentage breakdown of plant and equipment contract costs for an energy from waste plant based on mass burn incineration.

Cost item	**70,000 tonnes p.a.**	**200,000 tonnes p.a.**	**400,000 tonnes p.a.**
Residue disposal (£k p.a.)	756	960	1920
Labour (£k p.a.)	687	920	1149
Maintenance (£k p.a.)	643	974	1304
Consumables (£k p.a.)	221	629	1258
Insurance (£k p.a.)	89	108	216
Overheads (£k p.a.)	118	159	273
Management (£k p.a.)	35	60	100
Lenders fees (£k p.a.)	25	35	50
Total operating costs (£k p.a.)	**2,574**	**3,845**	**6,271**
Gate fee (£ per tonne)	**83**	**41**	**28**

Table 19 Estimates of the annual operating costs and gate fees for energy from waste plants based on mass burn incinerators.

Process	Capital costs (£ per tonne p.a. installed)
Compact Power	90-195
Pyropleq	110-310
Thermoselect	385-470
Von Roll	280-300
Mass burn incineration	200-350

Table 20 Capital cost estimates for energy from waste plants based on mass burn incineration and the novel thermal processes for MSW (Juniper, 2001)

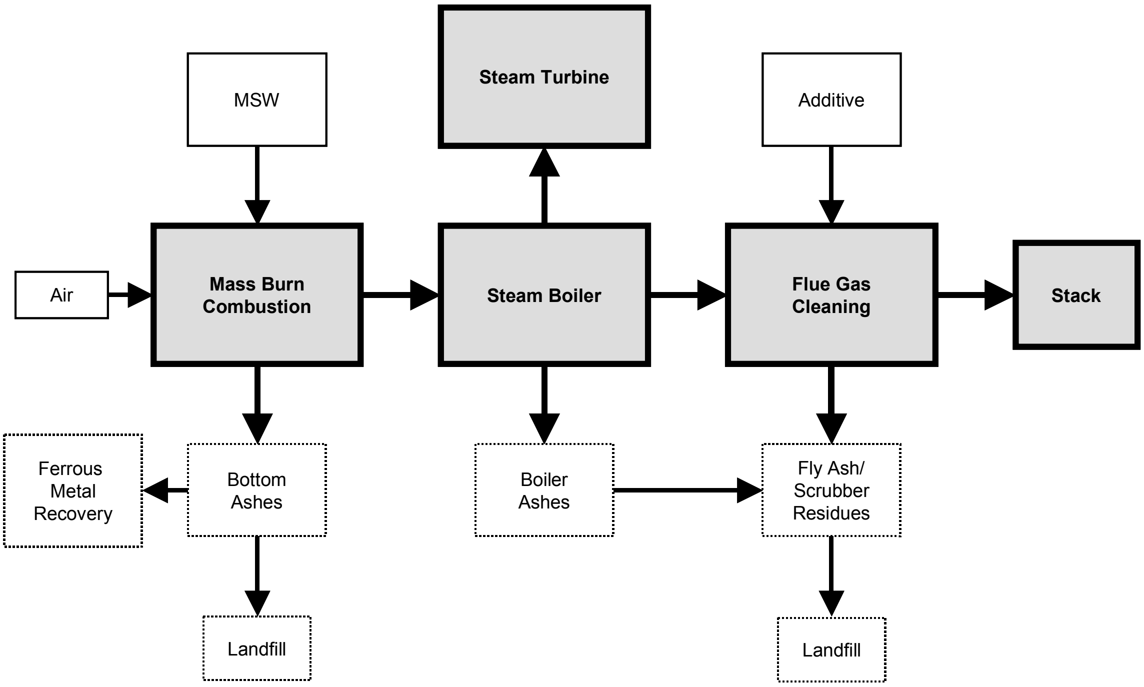

FIGURE 1 A simplified flow diagram for a mass burn incinerator

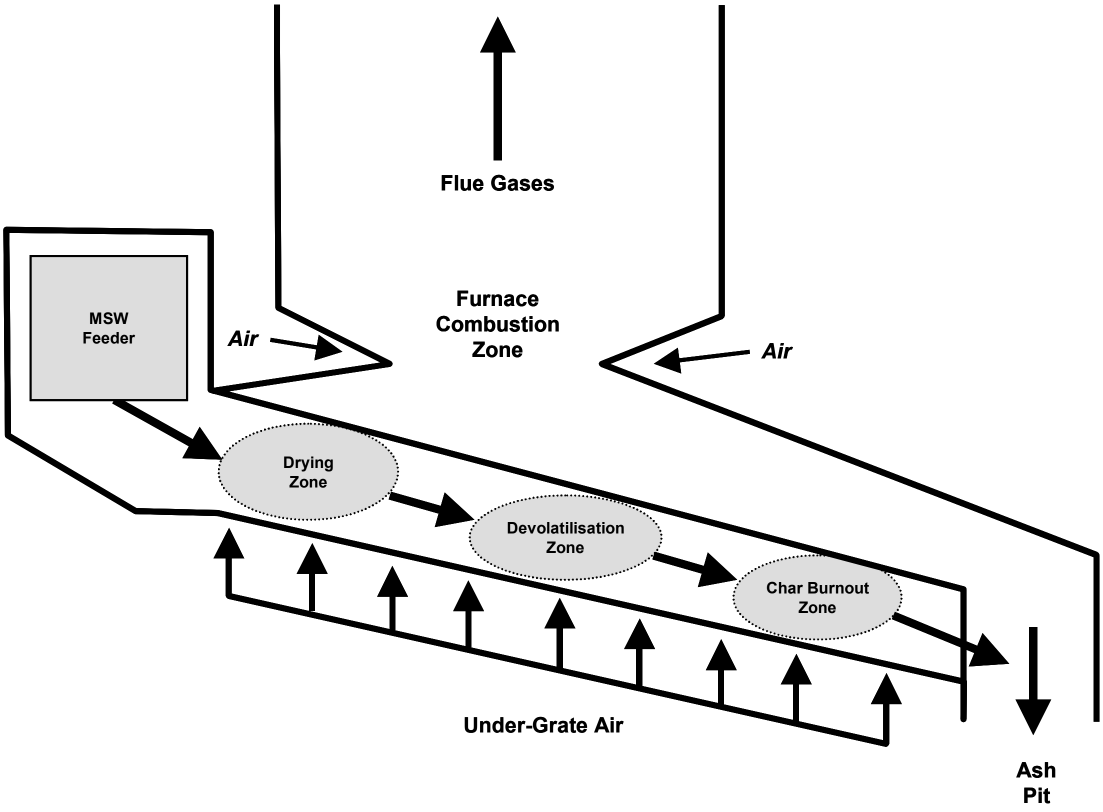

FIGURE 2 A simplified schematic diagram for the processes occurring in a mass burn incinerator

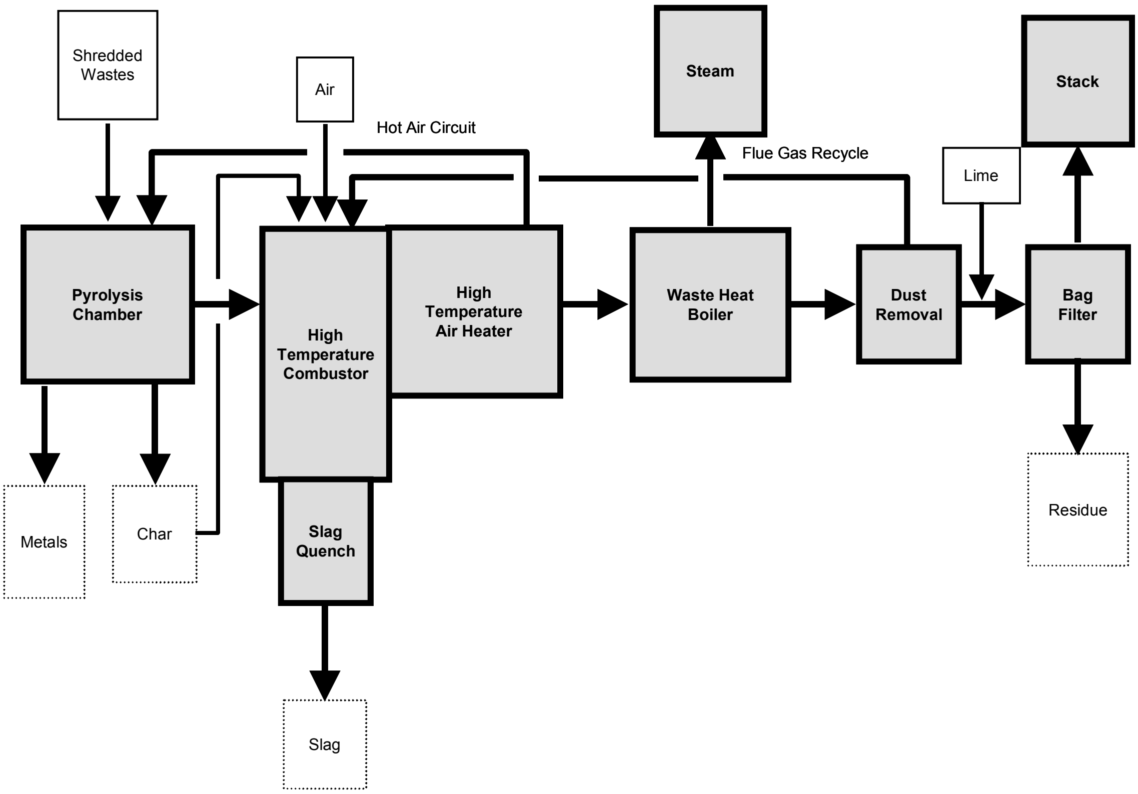

FIGURE 3 A simplified flow diagram for the Mitsui R21 process

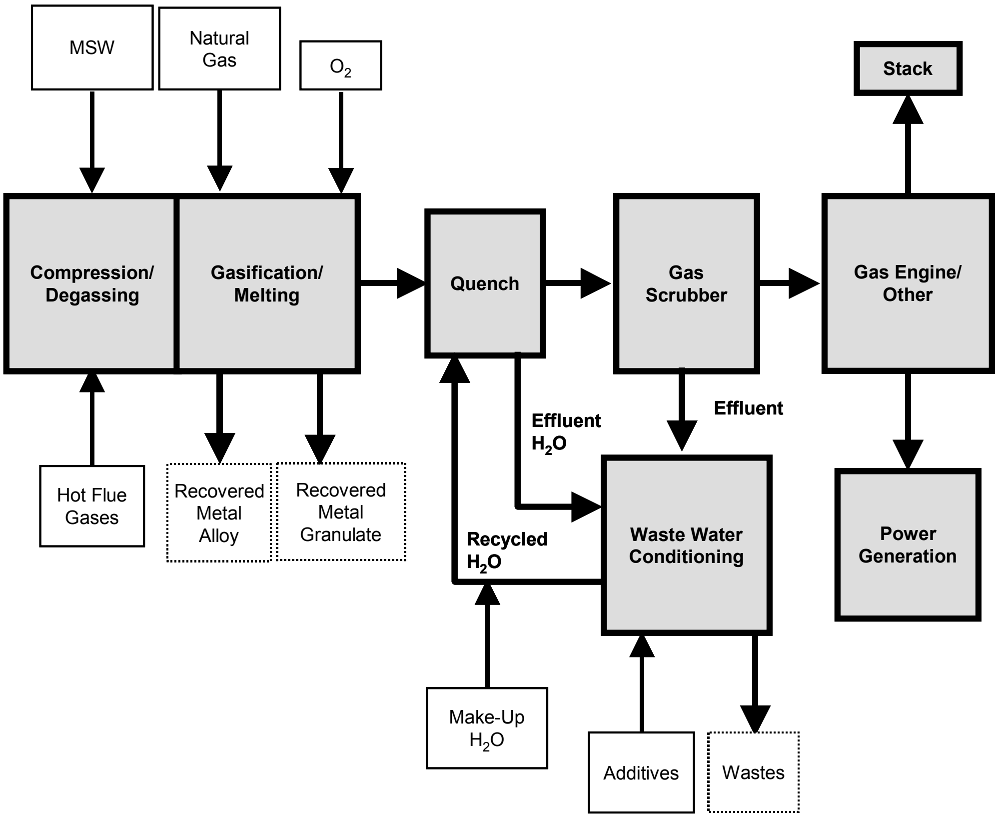

FIGURE 4 A simplified flow diagram for the Thermoselect process

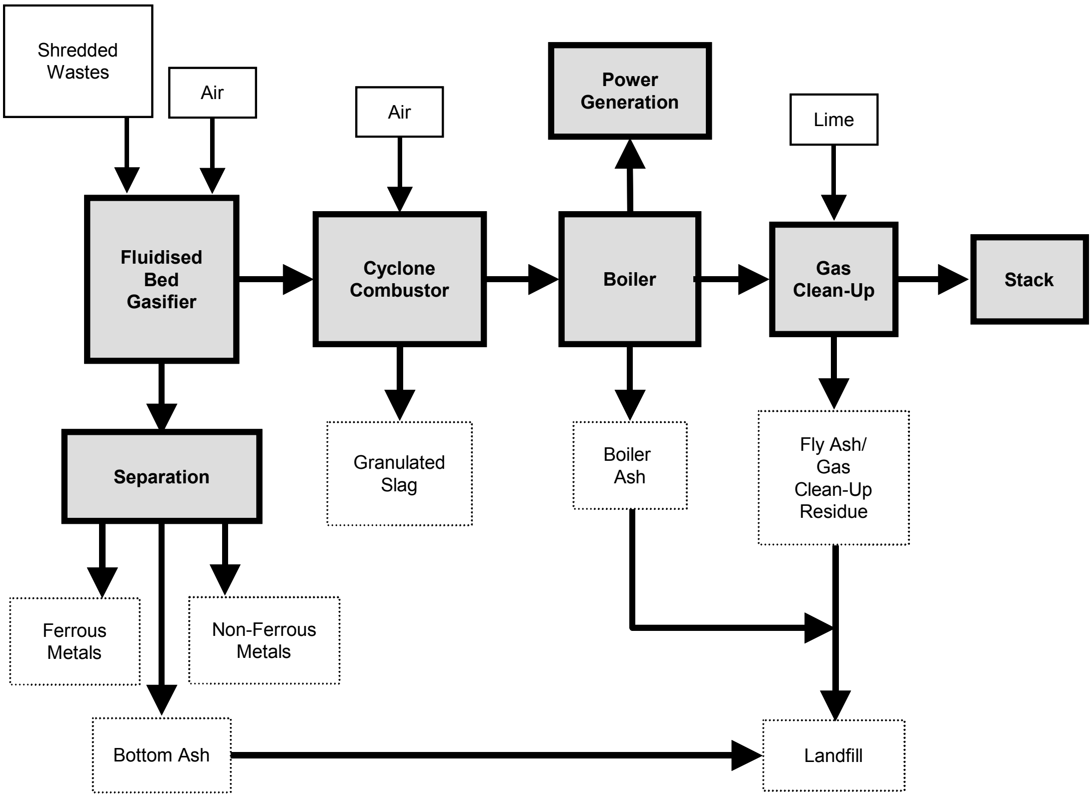

FIGURE 5 A simplified flow diagram for the Ebara TwinRec process

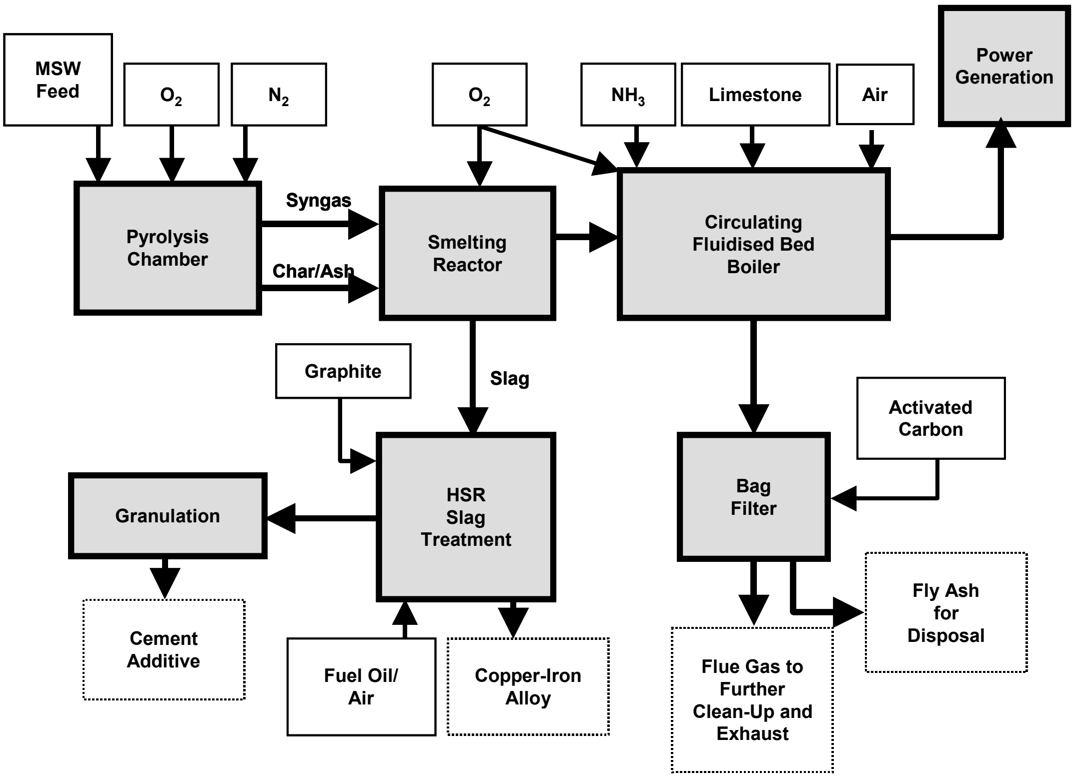

FIGURE 6 A simplified flow diagram for the Von Roll RCP process

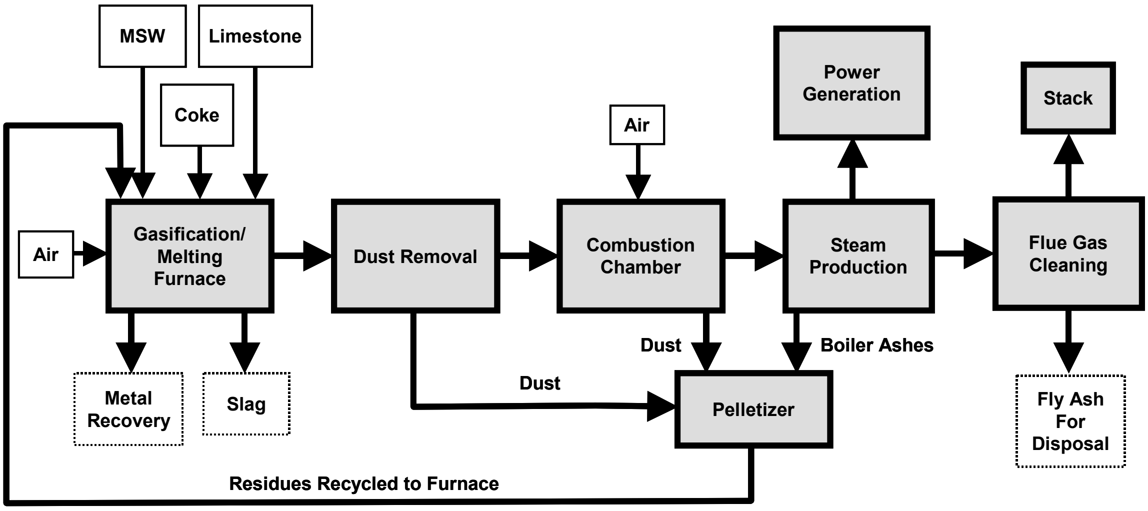

FIGURE 7 A simplified flow diagram for the Nippon Steel process

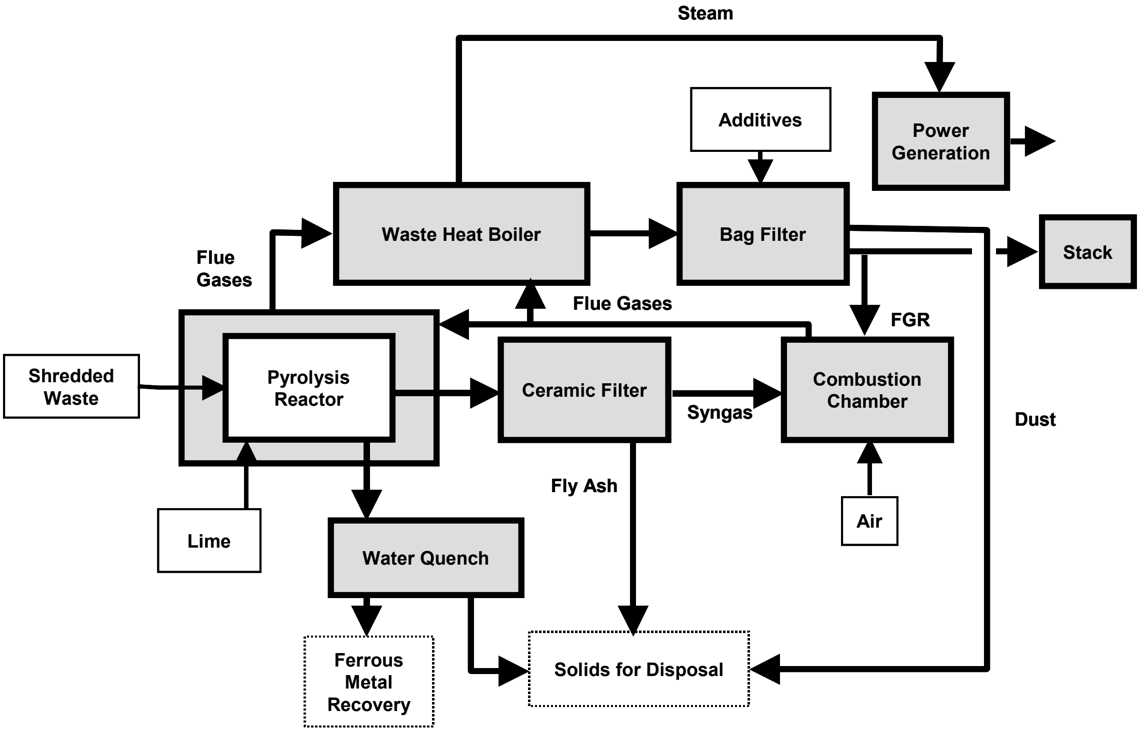

FIGURE 8 A simplified flow diagram for the Pyropleq process

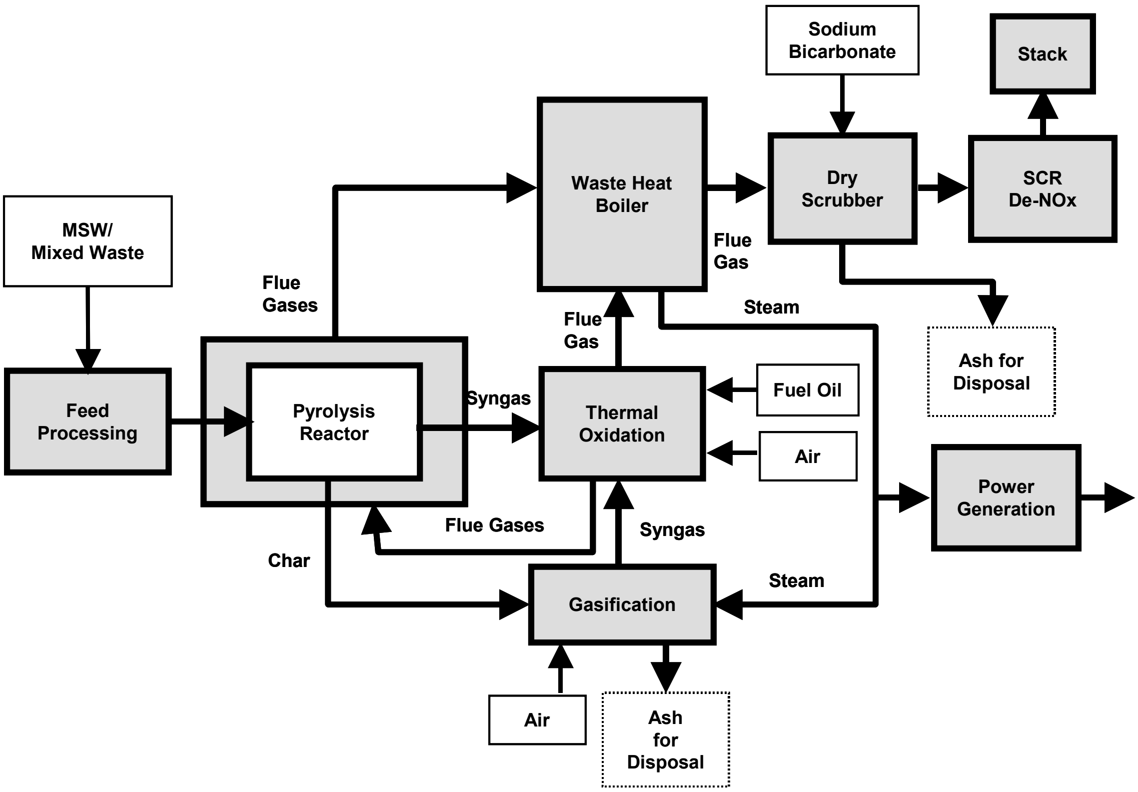

FIGURE 9 A simplified flow diagram for the Compact Power process