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REVIEW OF STATE-OF-THE-ART WASTE-TO-ENERGY TECHNOLOGIES

Stage Two – CASE STUDIES

January 2013

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| Checked by | Steven Wood | | | |
| Signature |  | | | |
| Authorised by | Kevin Whiting | | | |
| Signature |  | | | |
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REVIEW OF STATE-OF-THE-ART WASTE-TO-ENERGY TECHNOLOGIES

January 2013

Client

Waste Management Branch
Department of Environment and Conservation
Level 7, The Atrium, 168 St George's Terrace
PERTH WA 6000
AUSTRALIA

Consultant

Kevin Whiting
Senior Technical Director
WSP House
London
WC2A 1AF
UK

Tel: +44 (0)20 7314 4647
Fax: +44 (0)20 7314 5111

www.wspgroup.co.uk

Registered Address

WSP Environmental Limited
01383511
WSP House, 70 Chancery Lane, London, WC2A 1AF

WSP Contacts

Dr Kevin Whiting
Mick Fanning
Mike Wilyman

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Preamble

The utilisation of waste as a resource for the recovery of materials and energy is becoming an increasingly attractive option for local and national governments worldwide. Waste to Energy (WtE) can support the diversion from landfill of large volumes of residual municipal solid waste (MSW), that is waste which cannot be effectively recycled through materials recovery or recovered through biological treatment (such as composting). In this way it can also contribute to meeting current and future obligations under relevant regulations, such as the EU Landfill Directive. Waste to Energy also offers the significant potential to contribute to the mitigation of climate change, as part of Local and Regional Government energy strategies and policies to meet CO₂ reduction targets. Selection of the optimal WtE technology will require careful consideration of technical, environmental, regulatory and economic issues when evaluating life cycle costs and the impacts of WtE technologies.

Waste to Energy is the generic term given to a process by which the energy stored in waste (chemical energy) is extracted in the form of electricity, heat and/or a fuel for use in a de-centralised energy generation plant. A number of technologies are commercially available and have been deployed, especially in countries such as the USA, Denmark, the Netherlands, Germany, Switzerland and the UK. These represent a number of fundamentally different technologies under two main groups: e.g. biological processing of biodegradable waste and thermal technology of residual waste, including direct combustion (incineration), Advanced Conversion technologies (ACT - gasification and pyrolysis) or recovery of secondary fuel for subsequent energy recovery (SRF¹ from MBT² processes and biofuels from syngas produced by gasification processes). Maximising recycling and recovery from MSW³ and C&I⁴ waste will have both environmental and economic impacts on WtE technologies and considerable technological developments have been taking place within the WtE space to optimise the performance of state-of-the-art facilities.

This Stage 2 report provides a series of case studies highlighting modern state-of-the-art plants to support a joint review by the Western Australian Environmental Protection Authority and Waste Authority on the performance (environmental and health) of WtE technologies internationally. WSP has selected the plants to be showcased here using the following selection criteria:

- modern plants with higher than normal thermal efficiency;
- modern plants achieving low environmental impacts;
- plants gaining acceptance via innovative architectural treatments;
- modern plants employing state-of-the-art furnace design;
- modern plants employing alternative thermal technologies, such as fluidised bed and gasification.

The report comprises two sections:

- an overview of thermal technology types and techniques;
- 15 Case Studies.

WSP has chosen to include two Case Studies that include more than one technology in order to provide the reader with a fuller understanding of current technical developments whilst still including interesting operating plants with innovative design elements:

- a review of the status of slagging gasification technologies in Japan;

¹ Solid Recovered Fuel

² Mechanical Biological Treatment

³ Municipal Solid Waste

⁴ Commercial & Industrial

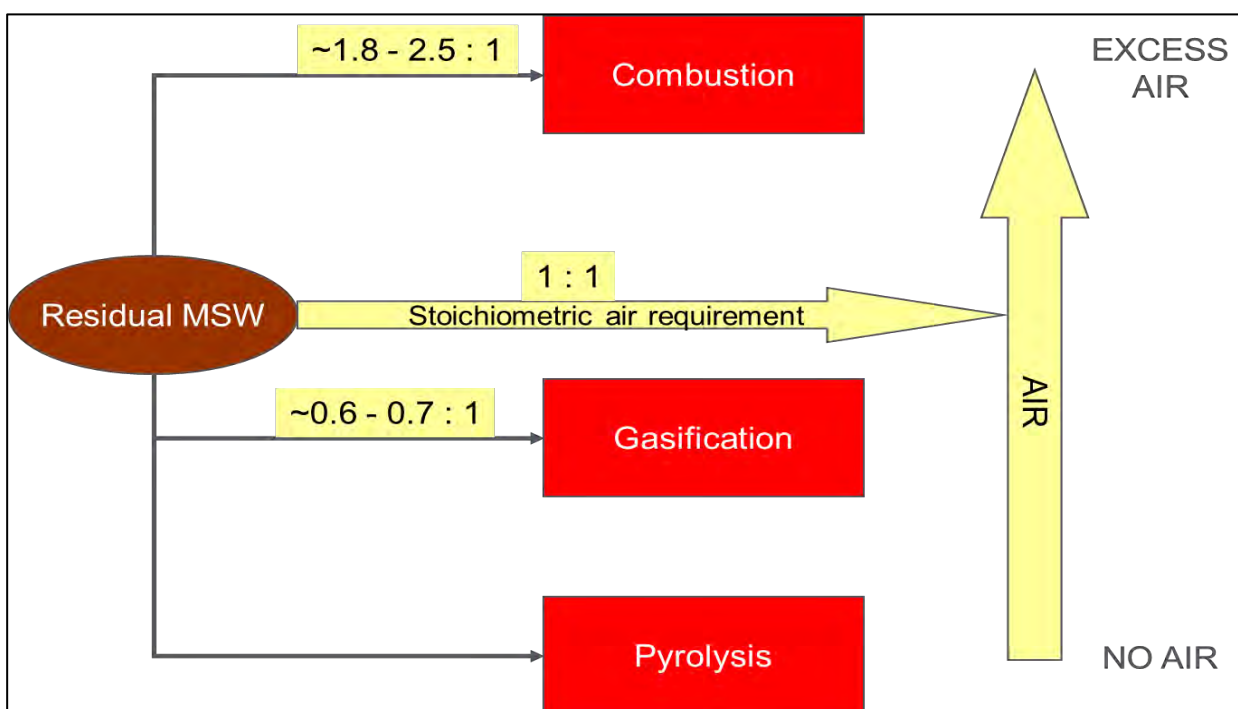
- a review of the status of plasma gasification technology developments.

In the accompanying summary report air emission performance versus WID limit values for each plant have been summarised in figure 1 and the technical parameters are provided in table 9 of the same report.

Overview of Thermal Treatment Technologies

Thermal conversion processes can be divided into three different categories; combustion, gasification and pyrolysis with each process being dependent on the concentration of oxygen. As can be seen in Figure 2-1 below; combustion takes place in an environment with an excess of oxygen, gasification is a partial oxidation process requiring an oxygen concentration slightly below the stoichiometric⁵ level. Pyrolysis occurs in the absence of oxygen.

Figure 2-1: Thermal Conversion Processes



The technology risk areas for WtE projects include:

- the availability of suitable feedstock for the duration of the plant's operational life?
- is the technology choice right for the feedstock?
- will the technology be capable of meeting all contractual targets and requirements of the client?
- the provenness of the technology solution?
- the flexibility of the technology with respect to changing waste composition?

⁵ The stoichiometric air (oxygen) requirement is the exact amount of oxygen needed to balance all of the chemical reaction equations to convert the C in the fuel to CO₂ and H to H₂O

- the technical/engineering and financial credibility of the supplier?
- the technical and financial credibility of the operator?

All of the above criteria need to be analysed and evaluated in great detail to ensure that the optimal technology is selected for the project.

What is Incineration?

Historically many commentators in the waste industry refer to 'mass burn' incineration as the thermal technology used for the conversion of solid waste into energy (power and heat). However, this terminology refers to technology of the past when the combustion unit received all types of wastes into the unit and combusted it with the primary goal to maximise the reduction in volume of the waste: i.e. 'to render the waste to ashes'⁶ without energy recovery.

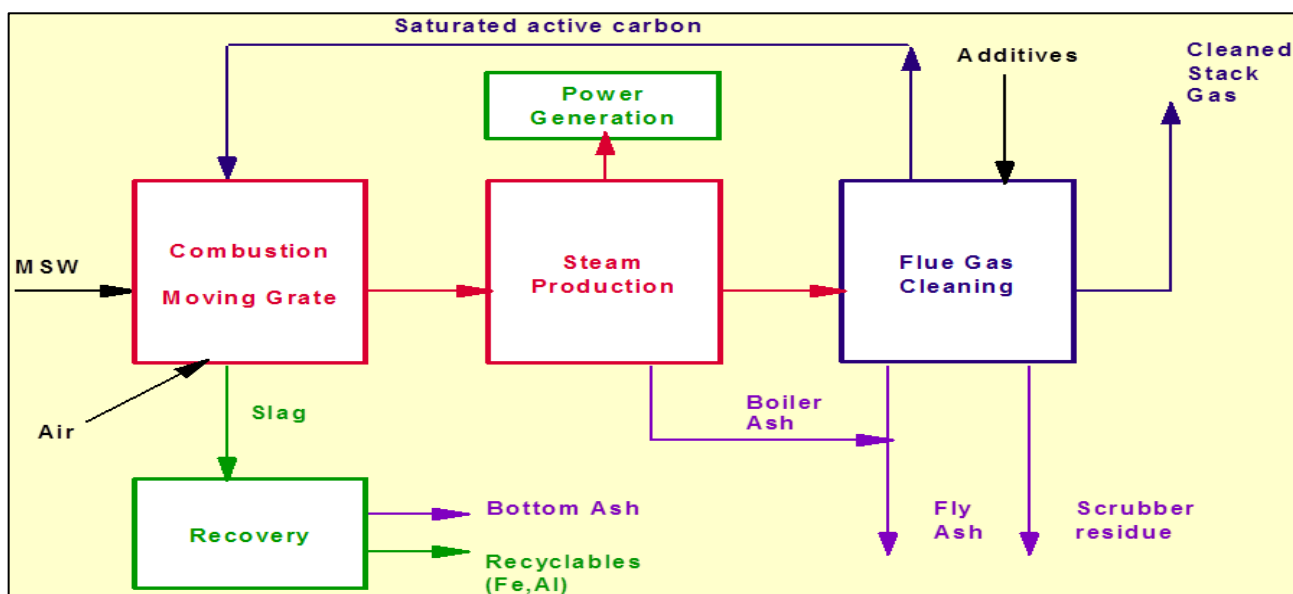
As a result of improved understanding of the combustion process (i.e.: health impacts) and the need to find alternatives to fossil fuels to mitigate climate change, Waste to Energy technologies and related legislation has been continually developed to provide a robust and efficient method of generating energy via the addition of energy recovery, the addition of flue gas treatment processes to meet regulatory requirements for emissions to air, improvements in combustion control, development of CFD⁷ techniques to determine the optimal injection points for secondary and tertiary combustion air and development of resource recovery options from the solid residues.

A large bank of detailed research now exists which reviews the health and environmental impacts of incineration. Stage 3 of the project provides a detailed summary of the research that has been carried out to consider the health impacts of incineration.

Moving Grate Technologies

Moving grate furnace technologies have been the 'workhorse' of waste thermal treatment with more than 1,000 operational plants worldwide. A schematic representation of a moving grate combustion plant is shown below.

Figure 2-2: Conventional Moving Grate Combustion Process



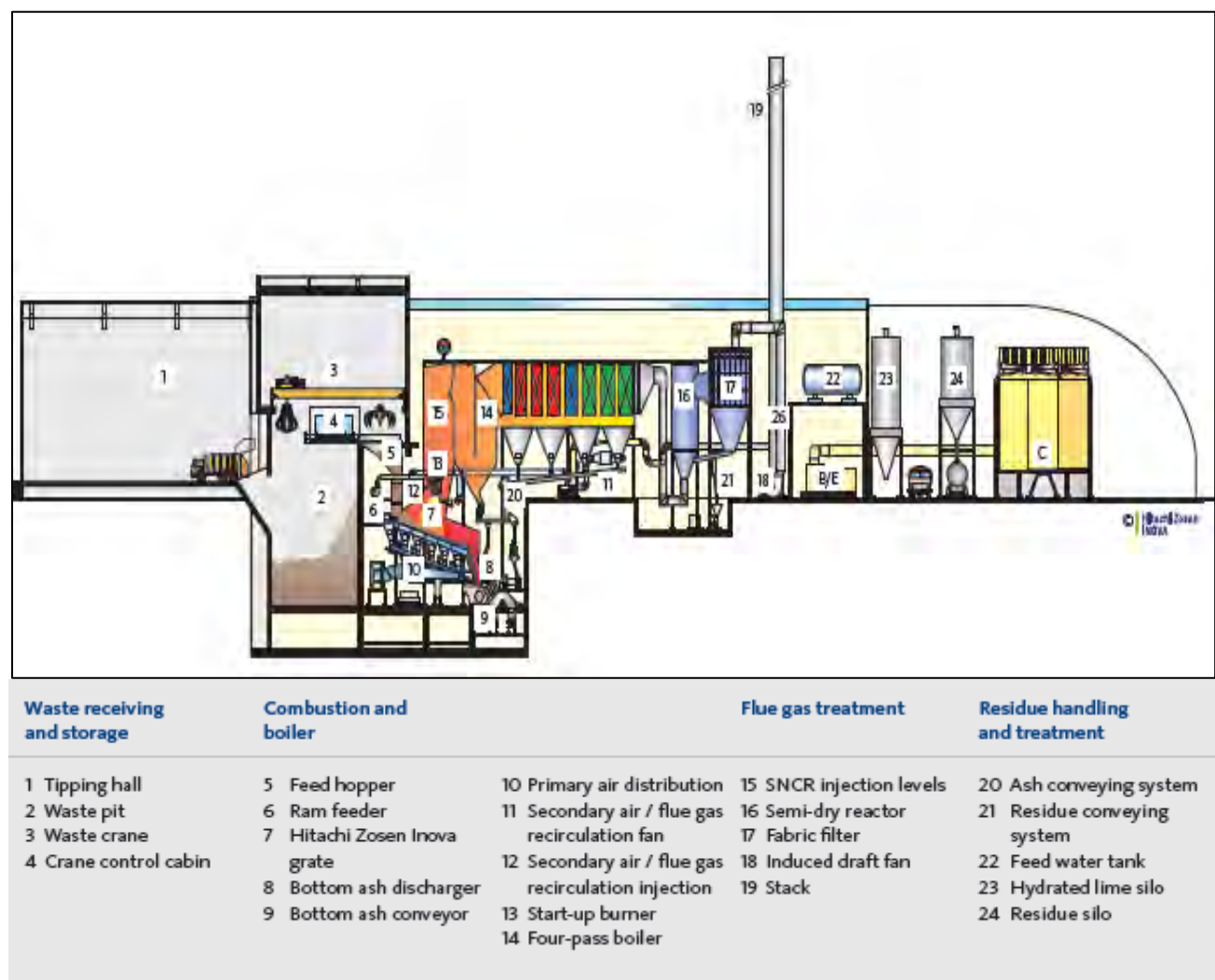
⁶ Oxford English Dictionary definition of incineration

⁷ Computational Fluid Dynamics

The moving grate mechanism (normally inclined although horizontal grate designs are operating) moves the burning solid waste from the inlet to the outlet. Primary combustion air passes from below the grate underneath the burning solids and flow through the waste bed into the freeboard zone above the bed. Secondary and tertiary air injection ports are used to ensure complete combustion of the gas phase components volatilised from the solid waste. Typical regulations require the flue gas to be held at a minimum temperature of 850°C for two seconds after the last injection of combustion air.

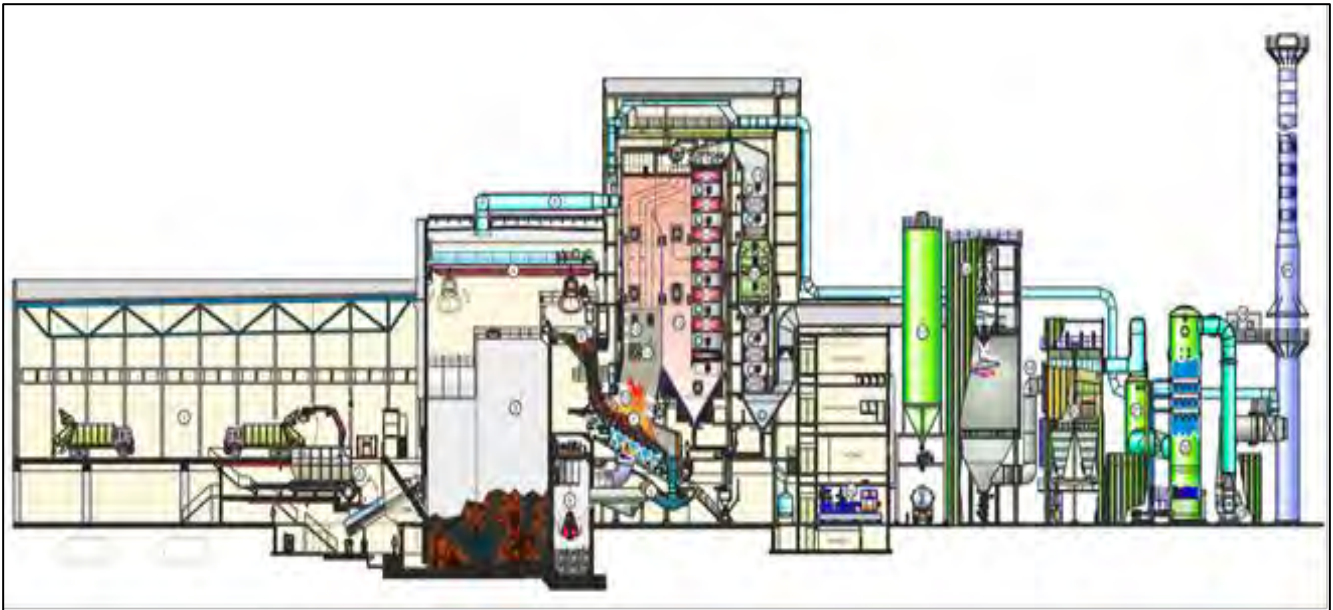
The hot flue gas then passes into the water tube waste heat recovery boiler. Various boiler designs have been used Figures 2-3 and 2-4 present cross-sections of typical WTE mass burn facilities that utilise horizontal (Figure 2-3) and vertical (Figure 2-4) boiler configurations.

Figure 2-3: Typical moving grate combustor with a horizontal boiler



Source: Hitachi Zosen Inova

Figure 2-4: Typical moving grate combustor with a vertical boiler



- | | |
|---------------------------------|--|
| 1. Unloading Hall | 14. Soot blower |
| 2. Shredder | 15. Slip catalyst converter |
| 3. Waste Bunker | 16. Turbine / generator for internal consumption |
| 4. Waste Crane | 17. Residue silo |
| 5. Under fire air intake | 18. Absorbers |
| 6. Feed hopper | 19. Absorbent injector |
| 7. MARTIN reverse-acting grate | 20. Fabric filter |
| 8. MARTIN discharger | 21. Pre-scrubber |
| 9. Bottom ash bunker | 22. Wet scrubber |
| 10. Over fire air system | 23. ID fan |
| 11. Ignition and support burner | 24. Measuring station |
| 12. NOx reduction (SNCR) | 25. Stack |
| 13. Steam boiler | |

Source: Martin GmbH

Both types of boiler configuration are capable of meeting all performance requirements and, by specifying the overall site space available, design/build vendors will configure all project components to make best use of the site space available. Table 2-1 compares the attributes of horizontal and vertical boiler configurations with the main difference being that horizontal boiler configurations consume more site space.

Table 2-1: Horizontal versus Vertical boiler configurations – pros and cons

| Horizontal boiler arrangement | Vertical boiler arrangement |
|---|--|
| <ul style="list-style-type: none"> ■ Meets current state-of-the-art design ■ Many reference plants worldwide ■ Meets all current guarantees ■ Employs mechanical rapping tube cleaning methods therefore lowers internal steam consumption ■ Requires more land take | <ul style="list-style-type: none"> ■ Meets current state-of-the-art design ■ Many reference plants worldwide ■ Meets all current guarantees ■ Employs soot blowers therefore steam consumption higher ■ Requires taller building ■ Lower investment cost |

Source: WSP analysis

Fluidised Bed Technologies

Fluidisation is the term applied to the process whereby a fixed bed of fine solids is transformed into a liquid-like state through contact with an upward flowing gas, usually air. The technology for fluidised bed (FB) combustion has been known for the greater part of the last century, though there were extremely rapid developments in FB technology during the 1970's throughout the world. Today, it is a well-established and proven process for energy conversion. The technology was originally developed for power generation from the combustion of coal but it has been applied to a much wider range of fuels in recent years. These include biomass fuels; such as bark, peat and wood chips, particularly in Scandinavia and Canada; and municipal solid wastes, in Japan.

Several gasification technologies use a fluid bed reactor and so consideration of the basic configurations that are common to combustion and gasification is necessary.

Figure 2-5: Conventional fluidised bed incineration process

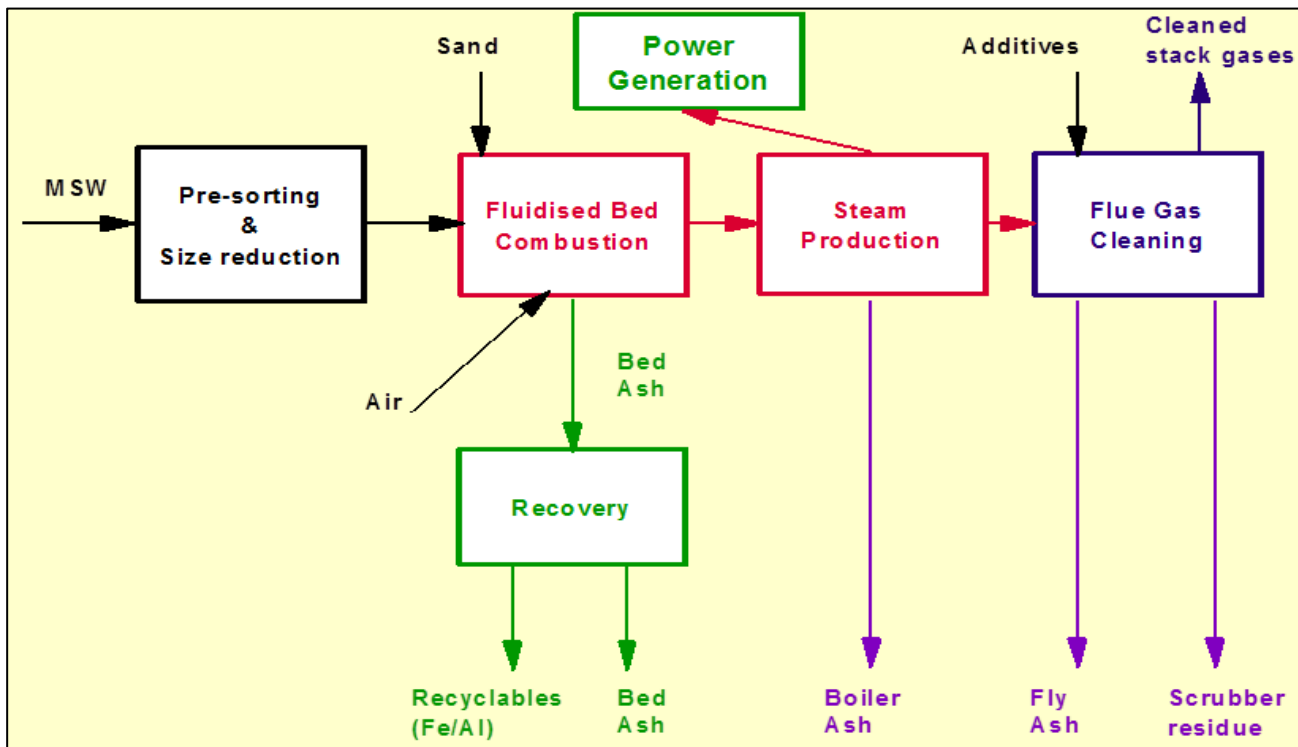
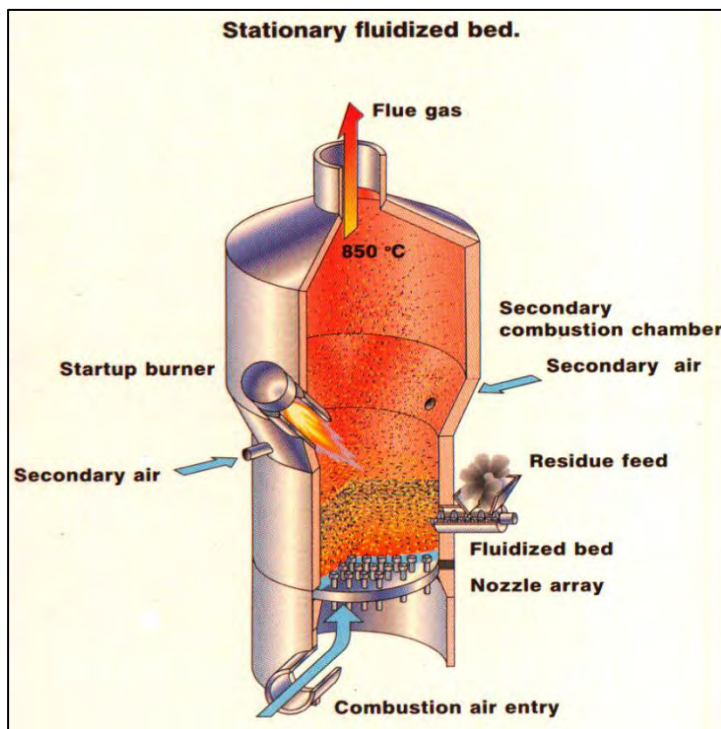


Figure 2-6: Schematic of a Bubbling Fluidised Bed Combustor

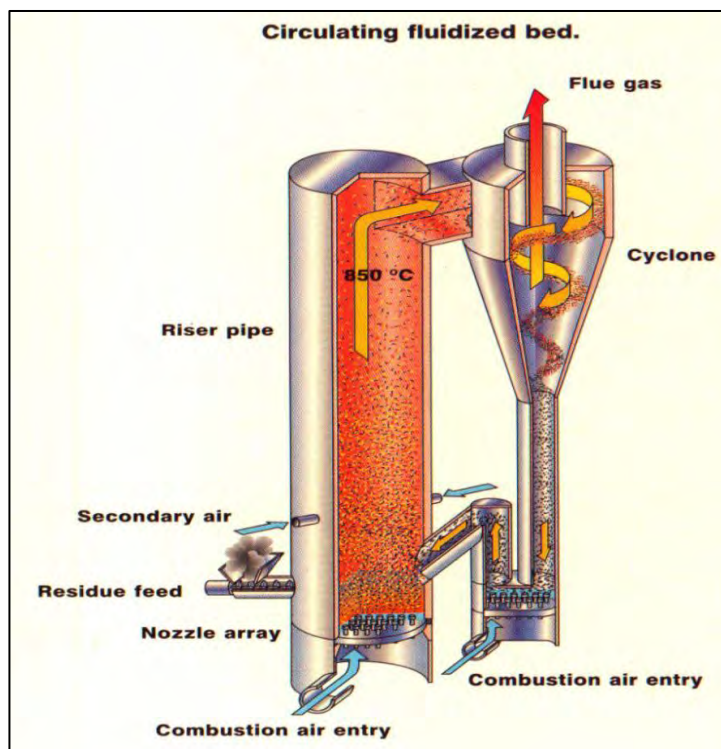


Source: Hitachi Zosen Inova

In a classical BFB the bed solids are large enough (approx. 750 – 1000 μm) and the gas velocity low enough (1 - 3 m/s) to ensure that all the particles, constituting the bed, are not entrained and carried out by the fluidising gas. Thus the bed operates below the minimum terminal velocity of the smallest particle in the bed.

The phenomenon of "bubbling" occurs at fluidising velocities above that required to fluidise the solids within the bed, with the excess gas above the minimum fluidising requirement, forming bubbles. These bubbles of gas can be seen to coalesce and grow as they rise rapidly through the bed. A "bubbling" bed resembles a violently boiling liquid. The presence of bubbles in the bed promotes intense circulation and mixing of the solids, leading to isothermal conditions throughout the bed.

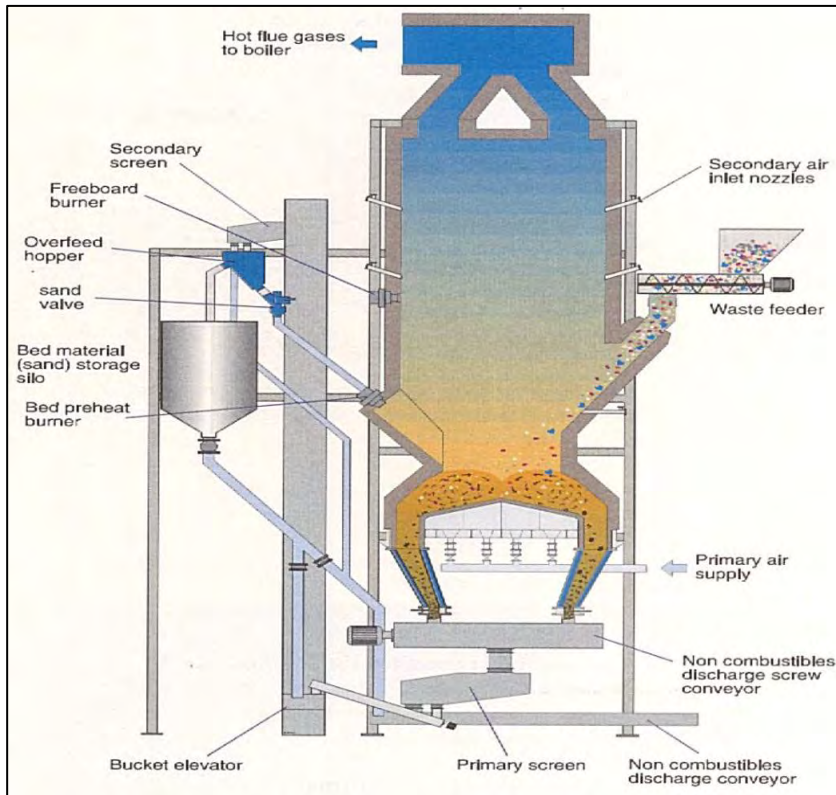
Figure 2-7: Schematic of a Circulating Fluidised Bed Combustor



Source: Hitachi Zosen Inova

As the fluidising velocity to a bubbling fluidised bed is slowly increased the bubble phase will disappear leading to a condition of uniformity, referred to as the turbulent state. If the gas velocity exceeds the transport velocity of the particles then, in the absence of solids recycle, the column containing the particles, would empty rapidly. However, if the solids ejected from the bed are captured in a cyclone and returned via a standpipe to the bottom of the bed then it is possible to maintain a relatively large solids concentration in the column. CFB combustors utilise smaller particles (approx. 250 μm) and higher gas velocities (5 - 6 m/s) than a corresponding BFB.

Figure 2-8: Schematic of the Revolving Fluidised Bed Combustor



Source: Ebara

The bed is retained within the combustion chamber as per the BFB, but circulation is introduced within the bed itself. This has the benefits of the high levels of turbulence within the CFB but in a smaller chamber. The technology was developed by the Ebara Corporation who has built more than 80 plants in Japan processing MSW or RDF. There are also 8 European plants that process MSW currently operating that were supplied under licence by Lurgi Lentjes (now Doosan Lentjes).

Table 2-2: Fluidised Bed (TIF) Combustion Reference Plants for MSW in Japan and Europe

| Plant Location | Country | Capacity (tpd per line) |
|----------------|---------|-------------------------|
| Various | Japan | ca 80 plants; 25 - 250 |
| Macomer | Italy | 72 |
| Madrid | Spain | 220 |
| Berlin | Germany | 200 |
| Gien | France | 120 |
| Mulhouse | France | 276 |
| Moscow | Russia | 320 |
| Macomer II | Italy | 72 |
| Antwerp | Belgium | 465 |
| Allington | UK | 505 |

Source: WSP analysis

Energy Recovery – Advanced Techniques to Boost Efficiency

In combustion processes (both grate and fluidised bed), hot flue gases exit the furnace and are used to generate steam. The gases exit at temperatures in excess of 850°C and pass through the boiler where heat is transferred to the superheater, evaporator and economiser tube bundles respectively. Superheated steam is transferred to a steam turbine generator where electricity is generated. Steam can also be extracted from the turbine at an intermediate lower pressure stage for process optimisation or to export offsite and supply a district heating network or feed an industrial need.

The steam conditions in a WTE combustion plant have typically been limited to 40bar, 400°C in most installations in Asia to avoid serious corrosion problems due to the high moisture content and plastics content of the waste; consequently, in conventional modern plants electrical efficiency is usually limited to around 22-25% (gross). There are a significant number of plants in the USA that operate boilers at 60 bar and plants in Europe have recently implemented similar high pressure boilers to increase the overall thermal efficiency of the WTE plant. This is discussed in more detail below.

In the last decade we have seen the introduction of a range of technologies designed to increase the electrical efficiency of WTE plants, particularly in Europe. This has been driven by the desire to increase revenue from electricity sales, and legislative requirements to demonstrate high efficiency to secure premium prices paid for electricity generated from renewable (or partly renewable) sources. Such plants are also supported by funding to assist with the additional capex, which has historically been a barrier to the implementation of more complex innovative solutions. There are a number of means by which the efficiency can be increased and these techniques have been developed by WTE suppliers, particularly for large scale moving grate combustion processes and this section summarises some of the technical approaches that been employed:

- **Advanced combustion control** – the use of enhanced process control will maximise combustion efficiency to ensure maximum burn-out of the organic waste content, reduced excess air levels; and optimum oxygen levels can be achieved using flue gas recirculation;
- **High steam pressure and superheat temperature** – increasing steam pressure and temperature will increase the enthalpy of the steam and allow greater energy to be recovered in the steam turbine. Extreme care with the boiler design needs to be taken to protect the superheaters and increase the overall thermal efficiency of the plant. Locating the superheater tubes in the furnace can also boost steam temperatures beyond that usually possible. The tubes require considerable protection (Inconel) to avoid major corrosion problems, and may be located behind protective tiles;

Table 2-3: Selected WTE Plants Employing high Pressure Boilers

| Plant | Steam pressure (bar) | Steam temperature (°C) | Efficiency (% gross) | Technique employed |
|--------------------------------|----------------------|------------------------|----------------------|--|
| Amsterdam (lines 5 and 6), NL | 130 | 440 | 30 | High steam pressure and temperature and reheat cycle |
| Brescia (lines 1 and 2), Italy | 61 | 450 | 27 | High steam pressure and temperature, superheater tube protection and CHP |
| Brescia (line 3), Italy | 73 | 480 | 28 | High steam pressure and temperature, superheater tube protection and CHP |
| Heringen, Germany | 81 | 520 | 29.7 | External steam superheating |
| Naples, Italy | 90 | 500 | 30.2 | Platen type superheaters with Inconel and SiC protection |

| Plant | Steam pressure (bar) | Steam temperature (°C) | Efficiency (% gross) | Technique employed |
|-----------------------|----------------------|------------------------|----------------------|--|
| Rudersdorf, Germany | 90 | 420 | 29.9 | High steam pressure and temperature and reheat cycle |
| Reno Nord, Denmark | 50 | 425 | 26.5 | High pressure steam and CHP |
| Riverside, London, UK | 50 | 427 | 27 | Superheater tube protection |

Source: WSP analysis

- **Reheat cycle** – using a reheat cycle can increase the efficiency by several percent. Steam from the outlet of the high pressure stage of the turbine is sent back to the boiler where it is heated back to the original temperature, before being expanded in the low-pressure stage. This is a relatively high cost option, so the balance between cost and benefit of increased electricity generation has to be considered carefully;
- **Reduced boiler exit temperature** – the boiler exit temperature is established by sizing of the economiser and is typically set well above the dewpoints for hydrochloric and sulphuric acids and moisture. Preventing condensation of acid gases reduces corrosion and preventing condensation of moisture prevents agglomeration of particulate on the boiler tubes. However, keeping the exhaust gas temperature well above the dew points means that energy recovery from the flue gases is reduced. Careful control and reduction of this temperature has been employed on recent plants to maximise energy recovery with additional corrosion protection provided in the economisers;
- **Reduced steam condenser pressure** – the condenser temperature has a strong influence on the plant efficiency, the lower the condenser temperature, the greater the pressure drop across the turbine which increases power generation. Water cooled condensers can create the lowest temperatures but air cooled condensers are used where no water cooling source is available. However where the temperature of nearby water bodies is too high, warmer water temperatures may not provide a significant improvement in power cycle efficiency and will not offset the increased maintenance effort of a pumped once-through ocean water cooling system;
- **Integration with fossil fuelled fired power plant (external superheating)** – there are some plants in Europe that are integrated with a gas turbine CCGT⁸ system using the high temperature exhaust gases from the GT to provide additional heat. This can help boost the efficiency of energy recovery from the combustion of waste;
- **Combined Heat & Power (CHP) operation** – the recovery of heat as well as electricity can produce the greatest increase in efficiency. Steam can be extracted from the turbine and used directly for process heating in industry or used to produce hot water for a district heating network.

All of the above techniques come at a cost, and there will always be a balance between additional capital, operational cost and increased revenue from electricity (and potentially heat) sales.

⁸ Combined Cycle Gas Turbine

Table 2-4: Technology Supplier Plant and Experience

| Technology Supplier | Grate Combustion System for MSW? | Fluidised Bed Combustion System for MSW? | Largest Process Line (Tonnes per day) | Number of Reference Plants |
|---|--|--|---|---------------------------------|
| Moving grate combustion systems | | | | |
| Martin | Reverse reciprocating grate | No | 1200 | 389 |
| Keppel Seghers | Multi-acting reciprocating grate (Dynagrate) and forward acting grate (Volund) | No | 800 | circa 35 |
| Fisia Babcock | Forward acting reciprocating (Steinmuller) and roller | No | 960 | 59 |
| Babcock & Wilcox Vølund | DynaGrate, Vølund grate | No | 640 | 50 |
| Hitachi Zosen Inova | Forward acting reciprocating (formerly Von Roll Inova, HZ was Japanese licensee) | No | 920 | Approx. 480 |
| Kawasaki Heavy Industries | Horizontal water cooled grate ('advanced stoker system') | No | 450 | 200 – 300 small plants in Japan |
| Mitsubishi Heavy Industries | Reverse acting reciprocating (Martin grate licensee) | No | ? | circa 250 |
| JFE | Horizontal stoker grate ('Hyper Grate Stoker') | No | 450 | 120 |
| Fluidised Bed combustion systems | | | | |
| Ebara | | 'TIF' FB incineration system | 500 | 90 |
| EPI Outotec | No | BFB | 250 | 3 |
| Metso Power | No | BFB | Relatively small | 10 |
| Metso Power | No | CFB | Relatively small and process other fuels with RDF | 4 |

Source: WSP analysis of various data sources

Flue Gas Cleaning Systems

Modern WtE combustion plants are required to meet among the most stringent emissions requirements of any industrial process. Concerns around airborne pollutants, in particular dioxins, have led to a considerable tightening in the environmental regulation of such facilities over the last few decades, and as a result the emissions to air from modern plants are very low. Some plants even claim to produce flue gases that are cleaner than the surrounding air.

In order to reduce pollutant concentrations to the necessary level, extensive cleaning of flue gases is required. A range of Air Pollution Control (APC) technologies are used, though some components are common to the vast majority of plants. The exact system used depends on the emissions limits in the jurisdiction where the plant is located (national and/or local), specific requirements of the process (such as space or height restrictions) and economic factors. In this section we discuss the most common abatement technologies used in modern WtE facilities.

The following pollutants in Table 2-5 are regulated in most countries, and all the major technology suppliers will be able to comply with the relevant emissions limits by the inclusion of a suitable flue gas cleaning system.

Table 2-5: Air emissions abatement technologies

| Pollutant | Typical Abatement Techniques |
|---|--|
| Particulates | Fabric filters, Electrostatic precipitators, Cyclones |
| Oxides of Nitrogen (NO_x) | Flue gas recirculation, SNCR and SCR |
| Acid Gases (Sulphur Dioxide, Hydrogen Chloride, Hydrogen Fluoride) | Wet, Semi-dry or Dry scrubbers, Fabric filters |
| Heavy Metals (Mercury, Cadmium, Lead, Copper etc) | Fabric filters, Activated carbon injection |
| Dioxins and Furans | Flue gas recirculation, Fabric filters, Activated carbon injection |

Source: WSP analysis

Flue gas recirculation (FGR)

FGR has been discussed previously as a means to lower the excess air rate, which increases thermal efficiency and reduces the size of the downstream gas clean-up equipment. A further advantage is that lower excess air rate results in less nitrogen passing through the combustion chamber, and therefore lower formation of thermal NO_x.

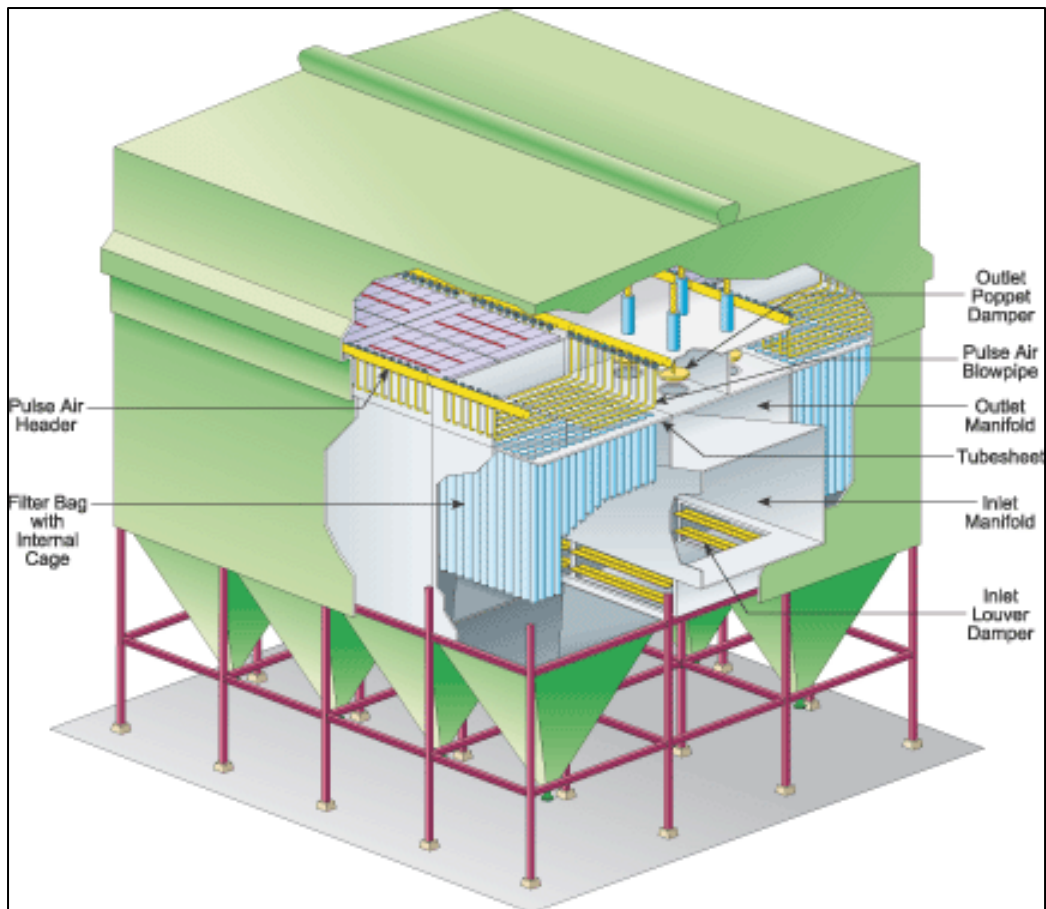
Particulate removal

Three devices are used to capture particulate matter from the flue gas stream. In general fabric filters are used in almost all modern WtE plants, as they have very high removal efficiency and also work in combination with scrubbing systems to optimise their performance at neutralising acid gases and removing other pollutants. Cyclones and ESP may also be used to capture particulate matter after the boiler where levels of entrained ash are high.

■ Fabric filter

A fabric filter consists of a large number of filter bags which capture particulate matter. Flue gas enters the base of the filter and flows through the individual bags. Particles are deposited on the outside of the bag and the cleaned gas flows through and exits the top of the unit. Fabric filters have a very high particulate removal efficacy, and are much more effective at removing fine particles than ESP and cyclones. They have an added advantage of providing a surface for the reactions to neutralise acid gases to occur. Hence they are usually located at the back of the APC system downstream of the scrubber. The layer of dust which accumulates on the filter bags is periodically removed using a pulse of air which rapidly expands the bag and dislodges the material.

Figure 2-9: Typical Fabric Filter (Baghouse)

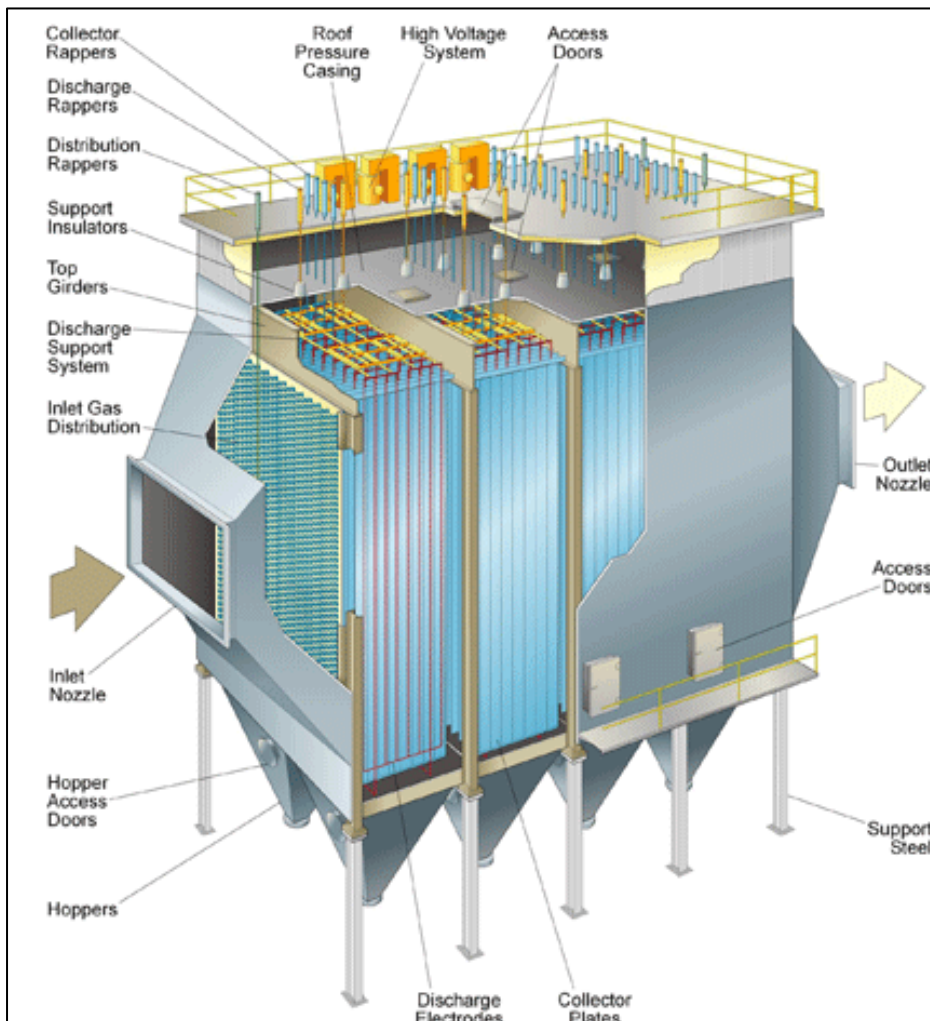


Source: Babcock & Wilcox Volund

■ Electrostatic precipitator (ESP)

ESP's have been used for many years on combustion plant, often as the only pollution control system on older incinerators. An ESP consists of two collector plates parallel to the flue gas flow, with charged wires hung vertically in the gas stream. The wires charge the particles in the flue gas flow, and the charged particles are then attracted to the collector plates. ESP is very effective at removing larger particulates, and is a robust unit which is simple to operate. However it has limited effectiveness at removing small particles and is generally insufficient as the only method of particulate removal, hence the preference for fabric filters on most modern plants. Some plants may use both types of system, particularly when located in regions with strict limits on particulate emission limits.

Figure 2-10: Typical Electrostatic Precipitator (ESP)



Source: Babcock & Wilcox Volund

■ Cyclones

Cyclones are another means of reducing particulates from the flue gas flow. However they are less effective than either the ESP or fabric filter. Some plants still use cyclones to remove larger fly ash particles, but require additional particulate removal, and few modern large scale WTE combustion plants incorporate cyclones in the gas cleaning system.

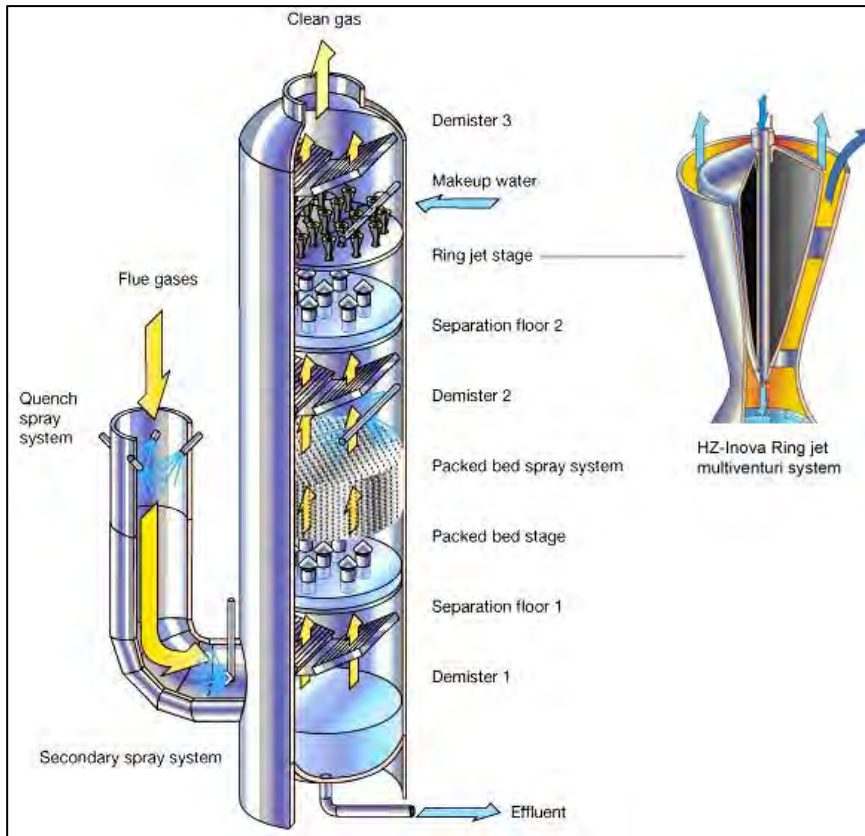
Acid Gas Scrubbing Systems

Acid gases are neutralised and removed from the flue gas via some kind of scrubbing unit, which may be of wet, dry or semi-dry type.

■ Wet Scrubber

The flue gases are brought into contact with water droplets and liquid reagents, and pollutant gases are absorbed. Typically this is a two-stage process, with flue gases first passing through a tower into which water is sprayed to remove hydrogen chloride and hydrogen fluoride, followed by a second stage which uses hydrated lime or sodium hydroxide to neutralise sulphur dioxide. The wet scrubber is effective at removing acid gases, but is less efficient in energy terms (due to the cooling effect of the water spray) and produces a liquid residue which requires treatment in a water treatment plant (which must be on-site if the water is to be discharged or the effluent will need to be tankered off-site).

Figure 2-11: Typical Wet Scrubber



Source: Hitachi Zosen Inova

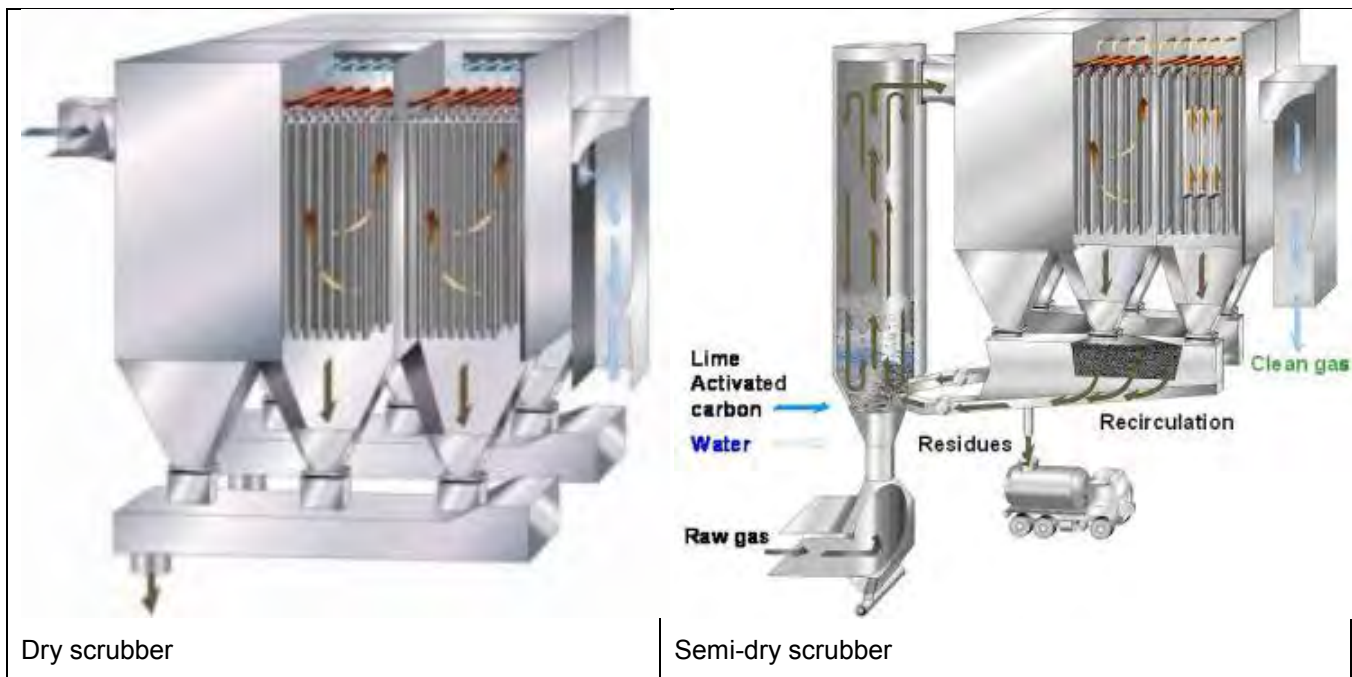
■ Dry and Semi-Dry Scrubber

Both the dry and semi-dry scrubber type also neutralise acid gases, but produce a dry residue. Dry systems inject dry powder directly into the gas stream, whereas semi-dry systems inject a hydrated slurry that on reaction with the flue gases produces a dry by-product.

In general hydrated lime or sodium carbonate is used as the reagent, and these systems are almost always used in tandem with a fabric filter which provides a surface for the reactions to take place (a process known as 'filsorption'). In both types of system the reactions take place at temperatures in the range of 120C to 180C

Dry or semi-dry filters are generally preferred as the dry residue is easier to handle, treat and subsequently dispose of.

Figure 2-12: Typical Dry Scrubber and Semi-Dry Scrubber



Source: Hitachi Zosen Inova

Heavy Metal and Dioxin/Furan Removal

Non-water soluble compounds such as volatile heavy metals (mercury, cadmium, lead) and dioxin/furans remaining in the flue gas stream are minimised by the injection of activated carbon. This material has an exceptionally high specific surface area and is very effective at adsorbing such compounds. Activated carbon is usually co-injected in a dry or semi-dry scrubber, or after the wet scrubber. In both cases the carbon and adsorbed compounds is captured by the fabric filter.

De-NOx Technologies

The combustion of waste produces NO_x by two means; via the combination of nitrogen and oxygen present in the air at elevated temperatures, and from nitrogen-containing compounds within the waste itself. Two techniques are used to minimise NO_x emissions from a WtE plant:

1. **Minimisation** of thermal NO_x - using combustion control and flue gas recirculation
2. **Reduction** of NO_x – using Selective Non-Catalytic Reduction (SNCR) and Selective Catalytic Reduction (SCR)

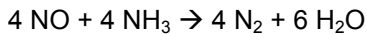
■ Minimising Formation of NO_x

The formation of thermal NO_x can be minimised by ensuring careful combustion control and reducing the excess air required for combustion. The following techniques can be used:

- Ensuring good mixing of waste in order that the feed to the combustion chamber is as homogeneous as possible
- Low excess oxygen (including use of flue gas recirculation)
- Stable, low temperature in the combustion chamber (an advantage of using a fluidised bed system)

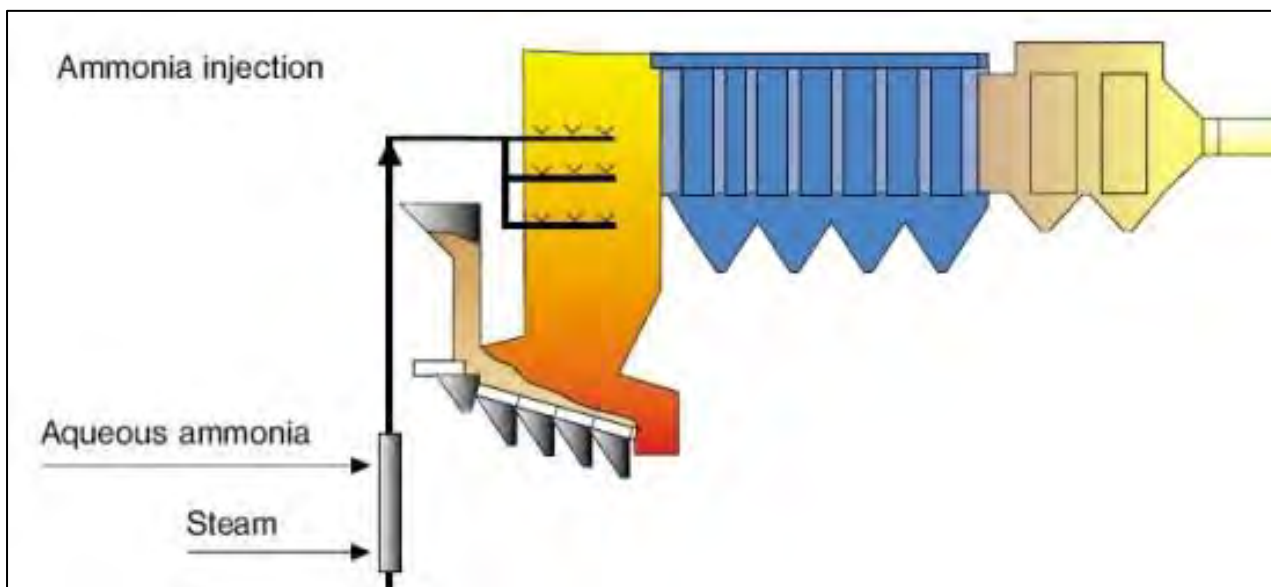
■ SNCR

NO_x can be reduced by the injection of ammonia (or ammonia-based compounds such as urea) into the flue gas at a temperature around 850 - 950°C. The ammonia reacts with a proportion of the NO_x to produce water and nitrogen, as per the following reduction reaction:



The high temperatures required for SNCR means ammonia must be injected into the upper part of the combustion chamber. The effectiveness of SNCR is limited by conditions in this region, and typically the maximum the NO_x emissions can be reduced by is around 60%. The quantities of ammonia required to achieve higher reductions lead to ammonia 'slip' (carryover of unreacted ammonia into the flue gas stream) and consequential undesirable emissions from the process (though it is possible to remove these if a wet scrubber is used).

Figure 2-13: SNCR System



Source: Hitachi Zosen Inova

■ SCR

SCR operates on the same principle as SNCR, but at a much lower temperature (200 – 300°C). This is achieved by the use of a catalyst to accelerate the reaction between the NO_x and ammonia at low temperatures. Higher NO_x removal is possible, but the costs are higher and the catalyst is sensitive to other pollutants and therefore the system usually needs to be located on the back-end of the flue gas cleaning system. The temperature range required for operation requires the flue gas to be reheated to at least 180°C before passing through the SCR unit and to the stack, and hence there is a loss of efficiency with this type of system.

The configuration of the flue gas cleaning system and the choice of equipment will depend on a number of factors:

- Emissions limits the plant must adhere to;
- Characteristics of the waste feedstock;
- Restrictions on space and other site-specific constraints; and,
- Economics.

This type of system is usually sufficient to meet emissions limits such as WID when using MSW as the feedstock, but where strict criteria exists additional particulate filtration or the use of SCR may be necessary for

example. Where very low emissions are desired or required, a wet system may be necessary, using an ESP, wet scrubber and fabric filter. However this has an energy penalty and requires water treatment plant. Furthermore, the plant footprint will be larger than for dry or semi-dry systems as the ESP is a bulky unit.

Availability and Reliability of Waste Combustion Plants

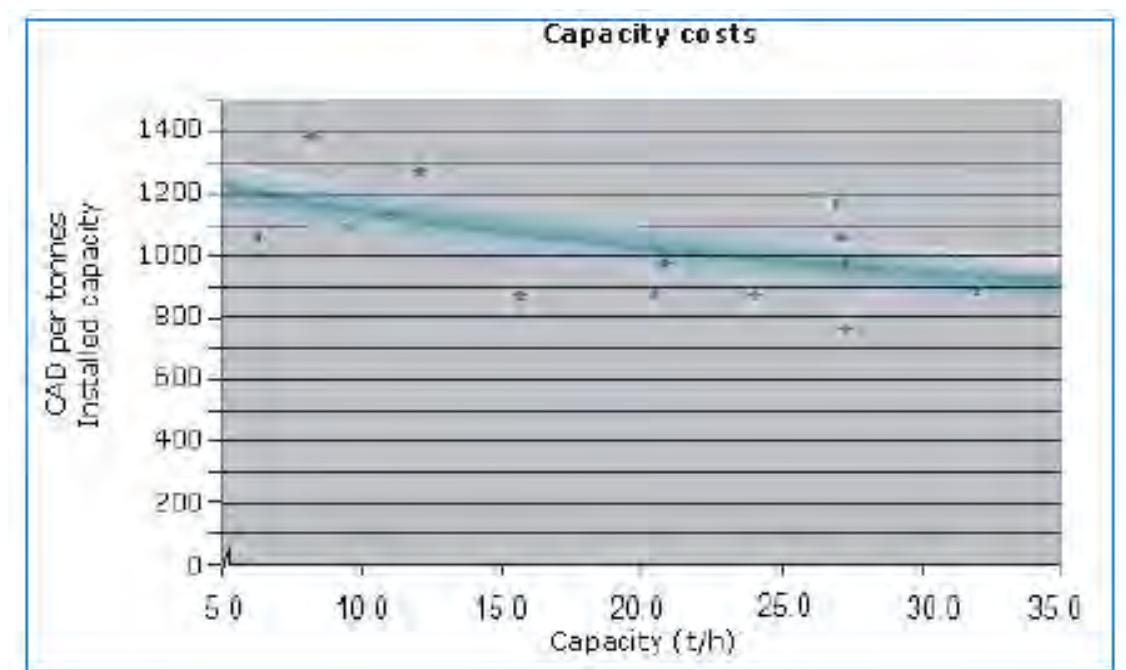
Large scale combustion is very well proven and high availability levels are possible, exceeding 90% in many instances and approaching 95% in the best performing plants. However, suppliers may not be willing to guarantee very high levels of availability, with 7,800 - 8,000 hours per year (89 - 91%) being common. All established suppliers should be able to provide guaranteed availability around this level. Some suppliers may guarantee in excess of 8,000 hours per year, but many would not be comfortable with this.

Capex and Opex Indicators for Waste Combustion Plants

Obtaining cost data from plant owners and operators is extremely difficult and comparing cost data across geographies is also an uncertain practice. The only true way to compare cost data is to develop project specific costings. However, we present here data from two credible studies to provide an indication to the reader of the orders of magnitude for capital and operating costs for WtE facilities.

1. *A Technical Review of Municipal Solid Waste Thermal Treatment Practices – Final Report by Stantec Consulting of British Columbia, Canada*

Figure 2-14: Comparison of Capital Costs (CAN\$) for WtE Facilities Per Installed Capacity



Source: Stantec Consulting

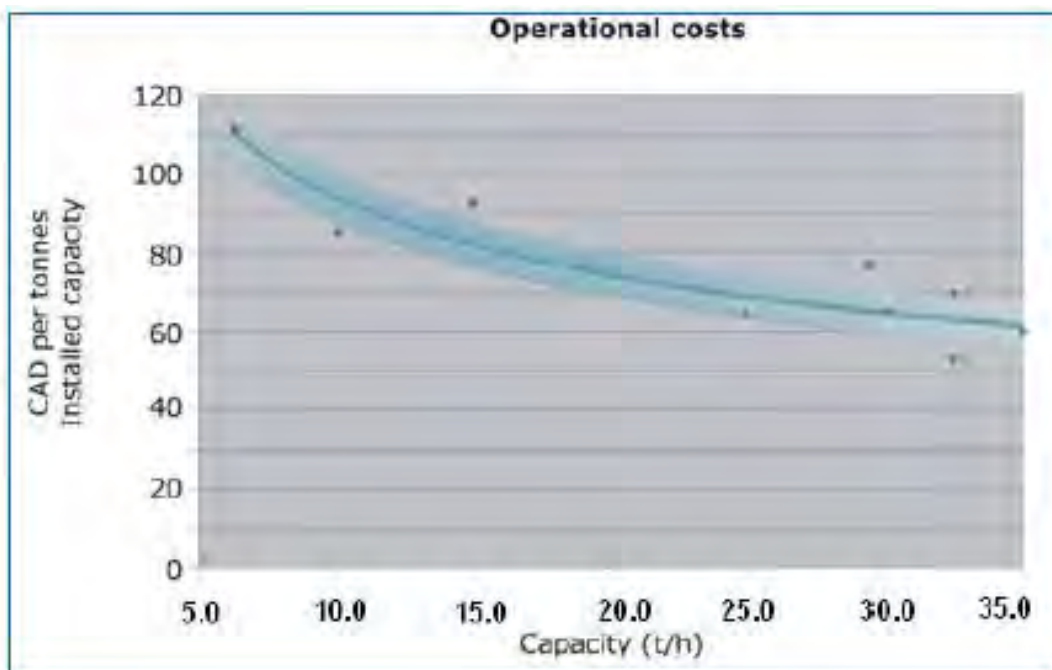
It should be noted that the capital costs in Figure 2-14 exclude the purchase of a site and exclude external infrastructure like roads, water, electricity/grid connections and all environmental planning and permitting costs.

Table 2-16: Typical Cost Build-up of WtE Plants

| Component | % of Capital Costs |
|--|--------------------|
| Thermal processing equipment (combustor/boiler) | 40 |
| Energy production equipment (turbine/generator) | 10 |
| Flue gas cleaning system | 15 |
| Building and civil works | 25 |
| Miscellaneous (approvals, general site works, ash processing, electrical transmission and grid connect, etc) | 10 |

Source: Stantec Consulting

Figure 2-15: Range of Operational Costs (CAN\$) for WtE Facilities in the EU



Source: Stantec Consulting

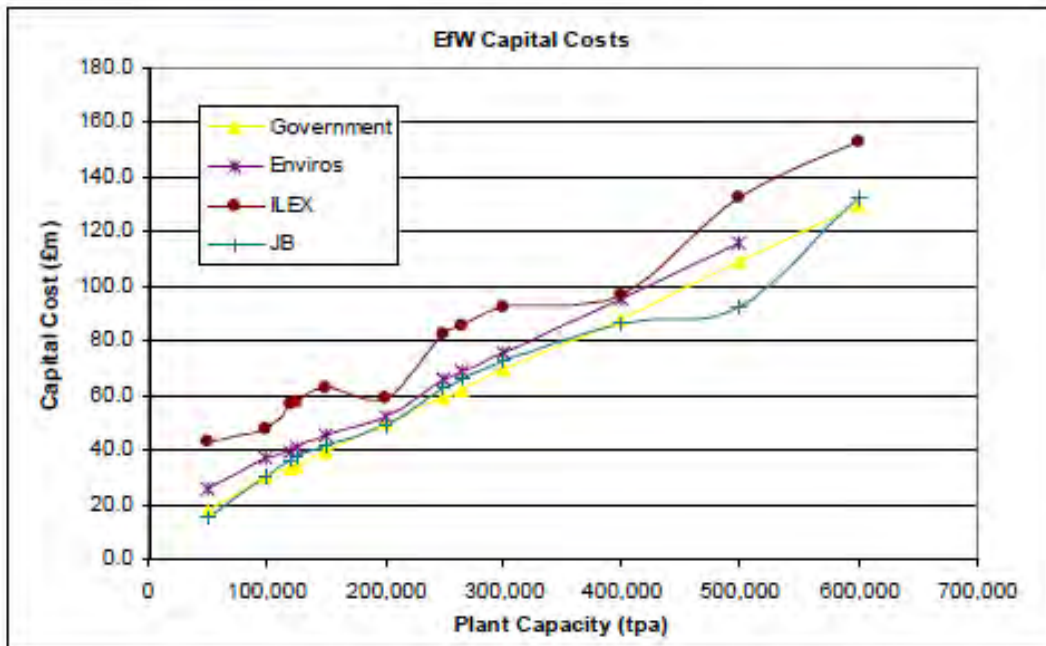
It can be seen from Figure 2-15 that the operational costs per tonne of waste processed, based on European price levels, are generally CAN\$60 – CAN\$90 per tonne of installed capacity. The operational costs between a small (6 tph) and a large (35 tph) incineration plant differs by almost 50% (on a cost per throughput basis).

The operational costs are typically split into different components:

- Labour and administration 25 – 30%;
- Maintenance 35 – 40%;
- Utilities and supplies – 20%;
- Residues (management and disposal) – 20%.

2. *Assessment of the Economies of Scale Associated with the Provision of Waste Treatment Facilities – Jacobs Babbie report for Kent County Council, UK, 2006*

Figure 2-16: WtE Capital Costs (GBP) vs. Plant Capacity (tpa)



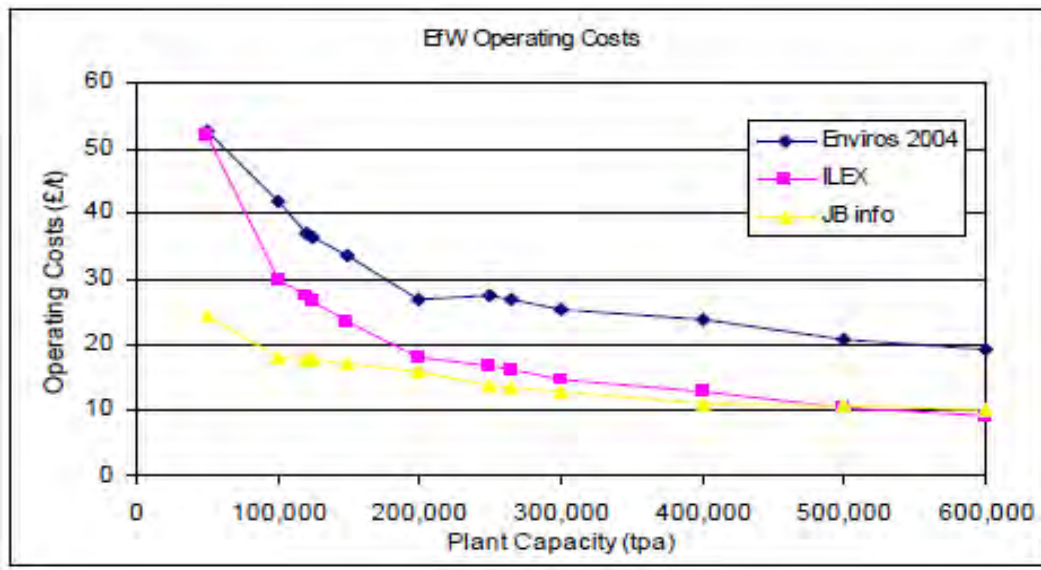
Source: Jacobs Babbie

From Figure 2-16, the relationship between capital cost and plant capacity is non-linear, i.e. the capital costs do not increase proportionately. This simply means that if the plant capacity is doubled, the capital costs do not double.

From the extrapolated data, the range of capital costs for a 125,000 tpa facility is £34.2m to £57.4m, and for a 250,000 tpa it is £59.3m to £82.4m. The underlying data yield arithmetic mean values of £42.5m for a 125,000 tpa plant, and £67.5m for a 250,000 tpa plant. Both ranges of capital costs have a standard deviation of £10.3m from the average, which gives an indication of the data dispersion.

If the combined capital cost of two 125,000 tpa facilities is compared with a single 250,000 tpa facility then the difference (potential saving) is, on average, £17.5m.

Figure 2-17: Extrapolated Operating Costs (GBP) for WtE Facilities vs. Plant Capacity (tpa)



Source: Jacobs Babbie

The major contributor to operating costs is manning levels and the larger the plant the less staff per tonne of throughput would be required.

Gasification Technologies

Gasification offers a range of advantages over direct combustion of the fuel because it translates about 80% of the chemical energy in the waste fuel into chemical energy in the gas phase. The resulting syngas can be utilised in a range of applications, including steam boilers and gas engines for conversion to heat and electricity with potentially increased efficiency.

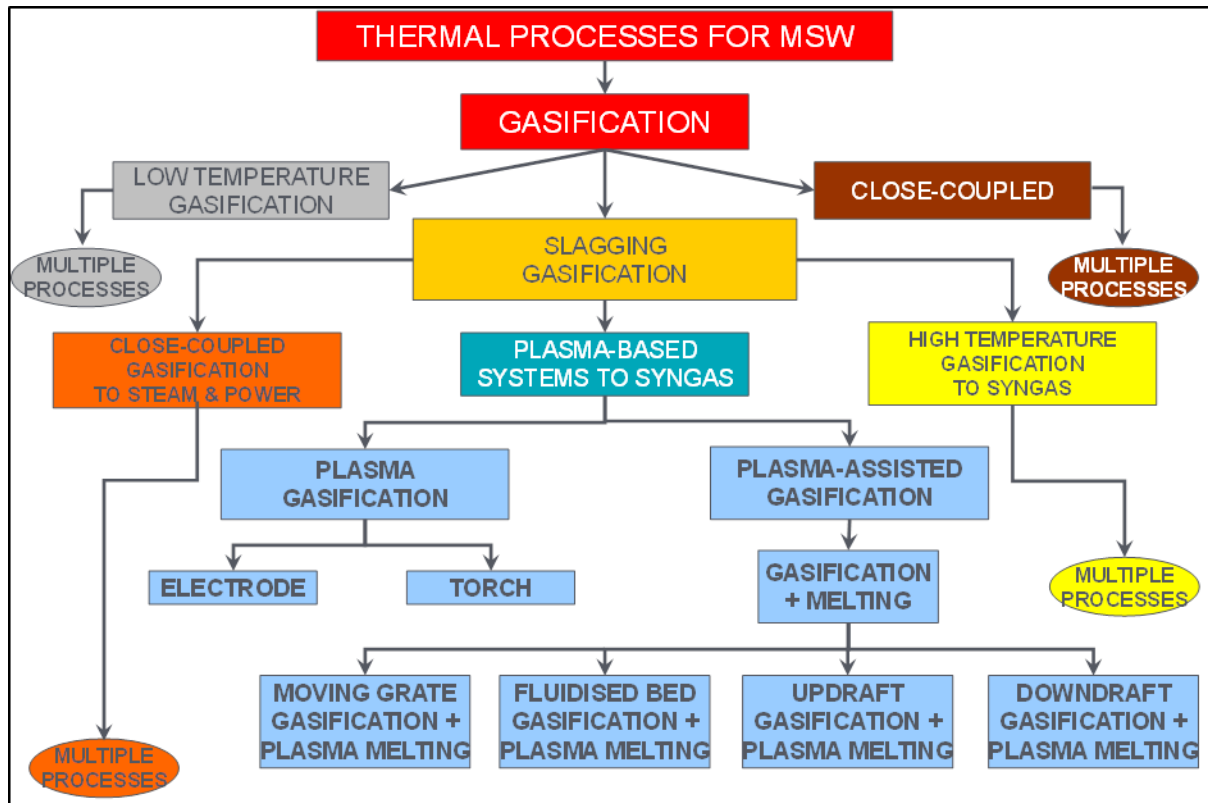
Gasification is a partial oxidation process, in which the majority of the carbon and hydrogen in the waste is converted into the gaseous form (called syngas), leaving a solid residue (ash or char). There are many different designs of the core gasification reactor such as fluidised bed, rotary kiln, updraft and downdraft reactors, each of which is tailored to give certain benefits when gasifying various types of wastes.

Relatively high temperatures are employed, 900-1100°C with air and 1000-1400°C with oxygen. Air gasification is the most widely used technology. It is cheaper but results in relatively low energy syngas, containing up to 60% nitrogen, with a heating value of 4-6 MJ/Nm³. Oxygen gasification gives a higher heating value syngas of 10-18 MJ/Nm³ but, of course, requires an oxygen supply. High temperature gasification also has the benefit of melting the ash (inorganic content of the input waste) to produce a slag, which is inert. The high temperatures necessary to melt the ash is produced either by oxygen injection or by the use of plasma to provide the necessary heat input (see Slagging Gasification and Plasma Gasification).

Pyrolysis, which is a word used interchangeably with gasification is a different process as we saw in Figure 1. It does provide other opportunities and this process option will be discussed in more detail later.

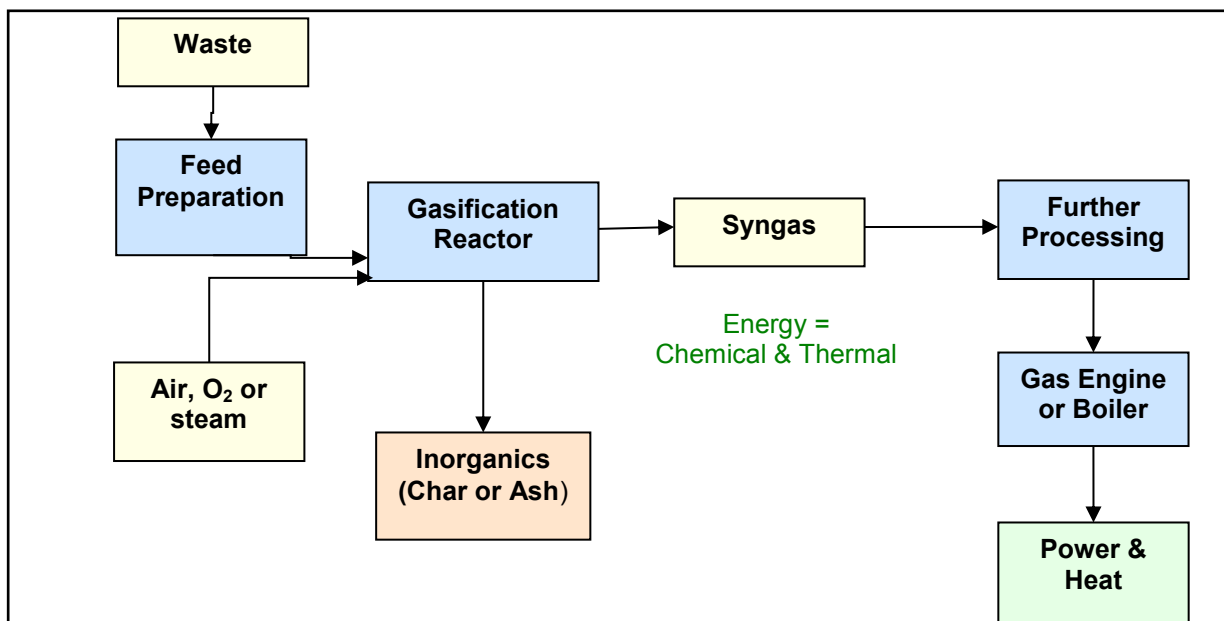
It is not a simple procedure to select the optimal gasification or pyrolysis process once the decision has been taken to utilise that family of technologies. There are a large number of different processes and process configurations that have been marketed as alternatives to incineration for treating MSW and residual waste, as can be seen from Figure 2-18.

Figure 2-18: Process configurations for gasification technologies



In gasification, the energy content of the waste is transferred into the gas phase as both chemical and thermal energy. The chemical energy makes it possible to store and utilise the syngas at a later time or elsewhere for power generation or via additional processing as a chemical feedstock.

Figure 2-19: Process schematic of waste gasification



There are a number of variants of gasification and pyrolysis reactor designs as shown below:

Table 2-7: Types of reactor employed for gasification and pyrolysis

| Reactor Type | Mode of Contact |
|--|--|
| <u>Fixed Bed</u> Downdraft Updraft Cross-draft <i>Variants</i> | Solids move ↓, Gas moves ↓, ie: co-current Solids move ↓, Gas moves ↑, ie: counter-current Solids move ↓, Gas moves at right angles ie: ← or → <i>Stirred Bed; Two stage gasifier</i> |
| <u>Fluidised Bed</u> Bubbling Circulating Entrained bed Twin reactor | Relatively low gas velocity, inert solid stays in reactor Much higher gas velocities, inert solid is elutriated, separated and re-circulated Usually there is no inert solid, has highest gas velocity of lean phase systems 1 st stage - steam gasification and/or pyrolysis; 2 nd stage – char combustion |
| <u>Moving Bed</u> <i>Variants</i> | Mechanical transport of solid, usually horizontal. Typically used for lower temperature processes, ie: pyrolysis <i>Multiple hearth, Horizontal moving bed, sloping hearth, screw/augur kiln</i> |
| <u>Other</u> Rotary kiln Cyclonic reactor | Good gas-solid contact High particle velocities and turbulence to effect high reaction rates |

Source: WSP analysis

Syngas contains CO (carbon monoxide), H₂ (hydrogen) and smaller quantities of CH₄ (methane) depending on the reactor type, as well as some of the unconverted reactants such as carbon dust, mineral ash, CO₂ (carbon dioxide) and N₂ (nitrogen) when air gasification is used. In addition, traces of other organic and inorganic compounds are produced or released in the gasification process and need to be cleaned from the syngas prior to utilisation.

There are a number of different ways in which gasification processes are configured. Some of the most common configurations use gasification in combination with combustion of the syngas; or pyrolysis in conjunction with gasification.

Gasification in combination with combustion has a number of advantages:

- the emissions of tar and volatile organics are minimised;
- the more conventional and proven steam boiler/steam turbine system can be used for energy recovery;
- the utilisation of well tried and tested flue gas cleaning methods to abate potentially harmful pollutants.

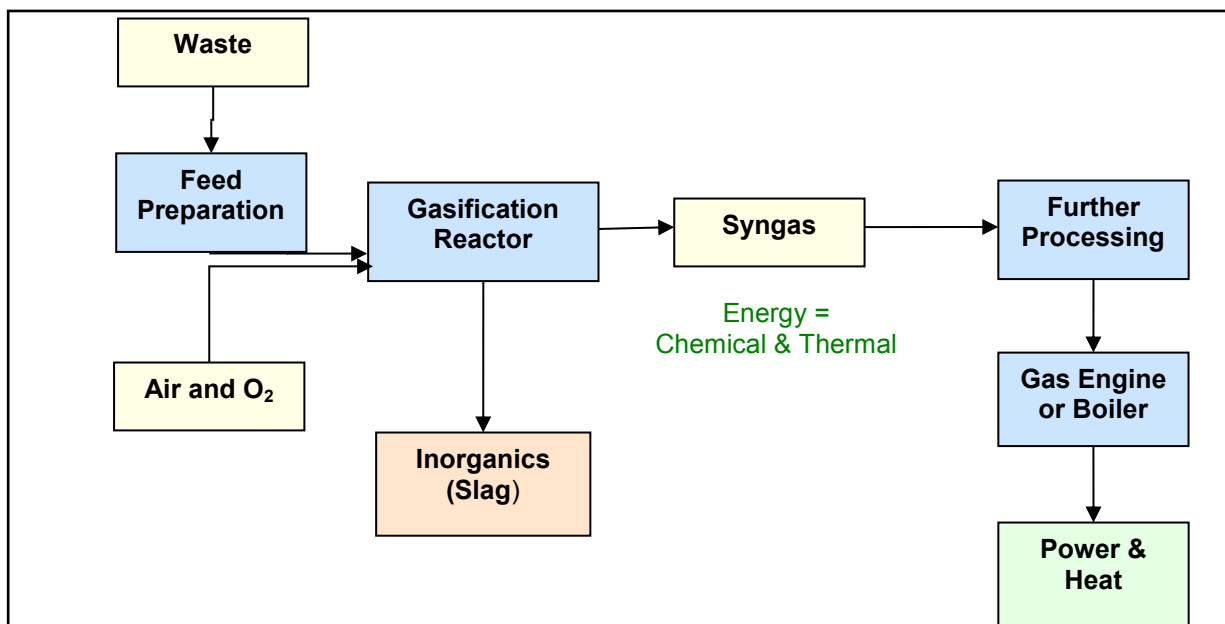
There are however a number of disadvantages with this approach:

- the process produces flue gas and therefore it cannot be configured to utilise more efficient energy recovery options such as gas engines;
- in this configuration the process is likely to have a larger plant profile than those configurations that produce a syngas because of the high flue gas volumes that may require a chimney similar in height to that of a moving grate energy-from-waste plant.

Slagging Gasification

Most of the gasification processes being operated in Japan are designed to melt the inorganics present in the waste because the main objectives are waste volume minimisation and maximised recycling. The resulting slag is inert and can be easily recyclable as a construction material. To slag the inorganic ash, high temperatures are usually required and this is facilitated by the utilisation of oxygen rather than air for gasification and/or the use of plasma processes to provide the necessary input of heat energy. The production of oxygen is costly and usually energy intensive although PSA (Pressure Swing Adsorption) systems are being used in Japan, which is much more cost effective than cryogenic air separation systems.

Figure 2-20: Process schematic of slagging gasification



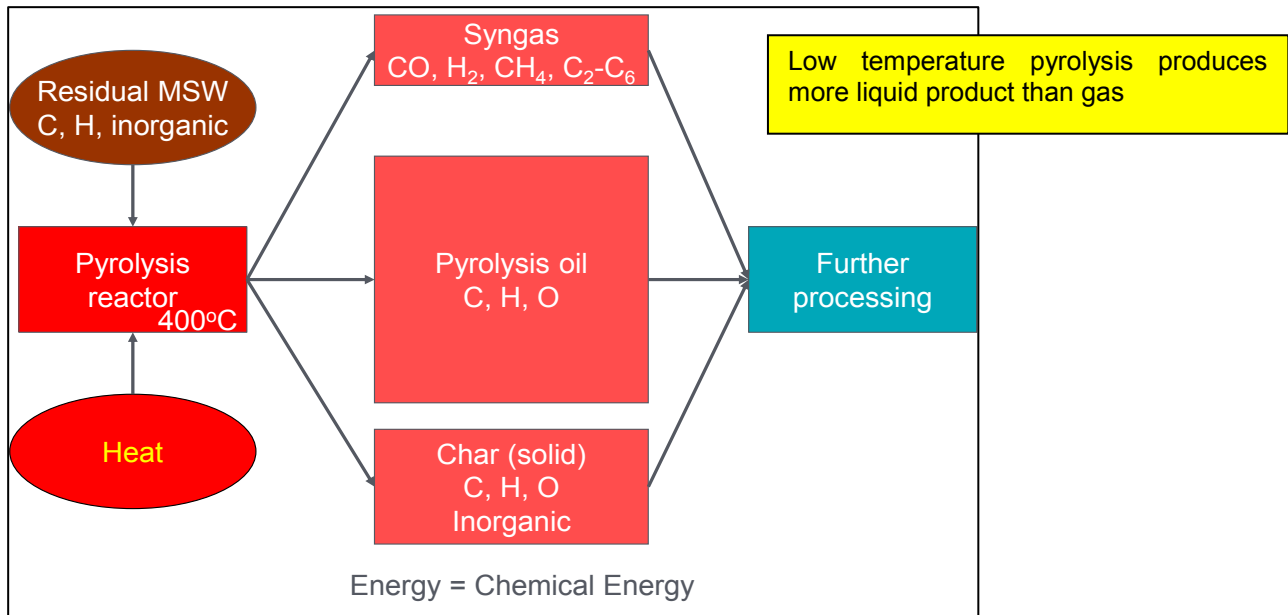
The majority of commercially sized operating facilities in the world, primarily in Japan, employ slagging gasification.

Pyrolysis Technologies

Pyrolysis is a process in which oxygen is excluded from the reactor, which is heated externally to produce the elevated temperature environment that causes the organic solids (waste input) to breakdown via physical and chemical processes into three products; solid char, pyrolysis oil and pyrolysis gas with the proportions of each being governed by the operating temperature within the pyrolysis reactor.

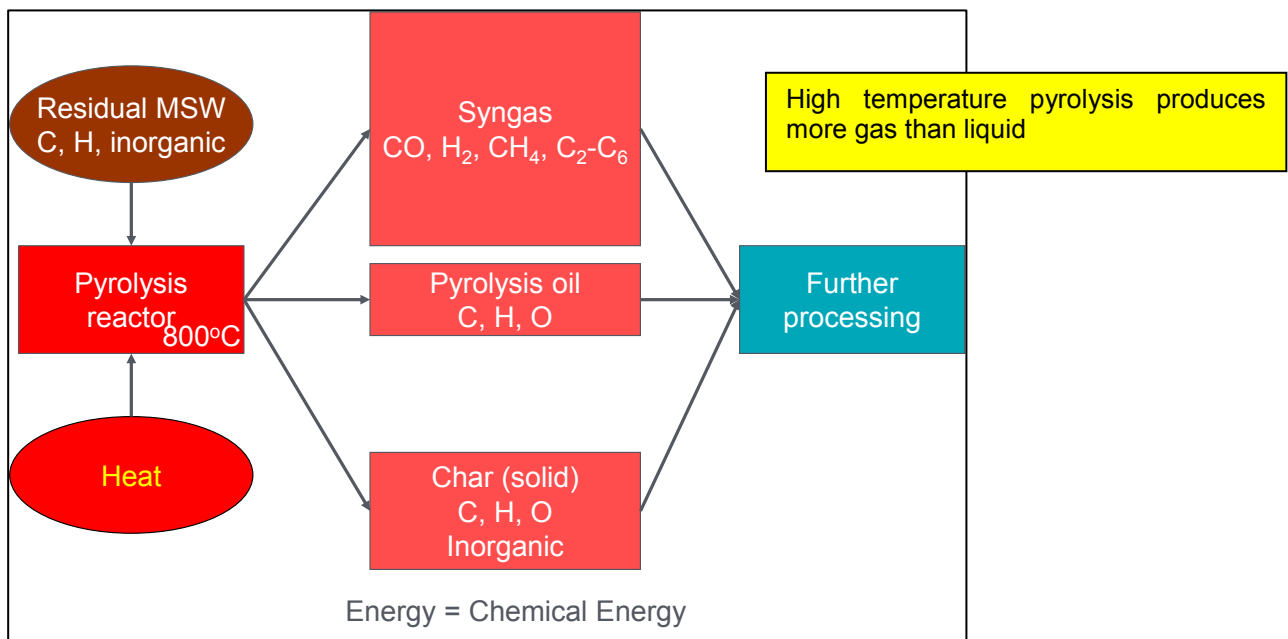
There is a certain amount of misunderstanding concerning the differences between pyrolysis and gasification with some people believing that they are the same. True pyrolysis is a low temperature thermal conversion technology that operates with an air free environment and produces a primary liquid product as well as gas and solid phase products. If pyrolysis is operated at high temperature (>800°C) then the primary product becomes syngas but the process will also produce liquid and solid phase products in lesser amounts.

Figure 2-21: Schematic representation of a low temperature pyrolysis process



By increasing the operating temperature the thermodynamics governing the reactions taking place cause a greater production of pyrolysis gas (syngas) at the expense of pyrolysis oil. The quantity of char produced at low and high temperatures does not vary greatly.

Figure 2-22: Schematic representation of a high temperature pyrolysis process



For biomass processing the lower temperature pyrolysis processes have been used with the objective of maximising the production of pyrolysis oil, referred to as bio-oil, which was seen as a pre-cursor to the production of many other chemicals in a bio-refinery context.

In a waste processing context the higher temperature pyrolysis processes have been developed in order to maximise the production of syngas, which is more easily converted to electricity. It is these processes that we

will consider in this report and we will refer to them henceforth as gasification as the sole objective is to produce syngas like gasification.

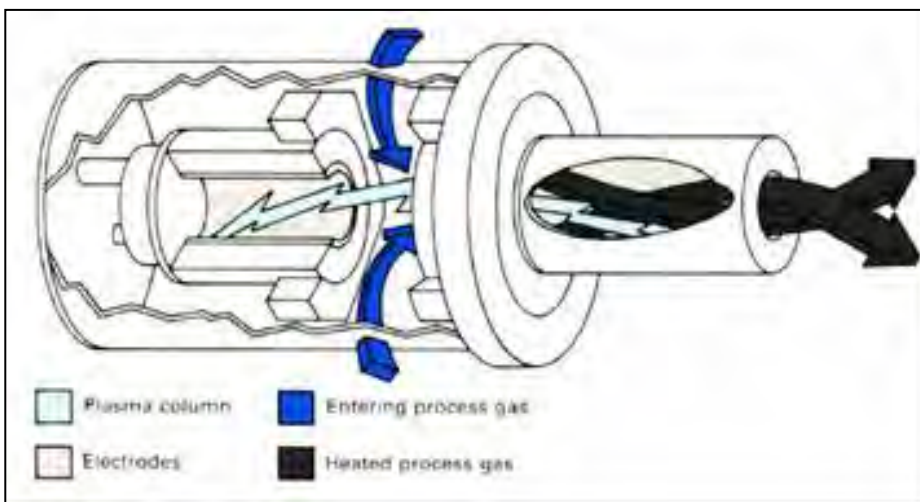
Plasma Gasification Technologies

Plasma involves complex science, but its application for treating waste is relatively straightforward: - it utilises high temperatures to convert waste into gases, a glass-like vitrified⁹ solid called a slag and molten metal.

Plasma is generated when gaseous molecules are forced into high energy collisions with charged electrons resulting in the generation of charged particles. This occurs when a gas (many types can be used and are sometimes referred to as 'carrier gases') is exposed to high energy fields such as an electrical discharge¹⁰ that can occur between two electrodes. When the quantity of charged particles (both negative and positive) is sufficiently high, the gas conducts electricity. Collisions between charged particles also occur giving off heat and an arc of light (similar to lightning) called Plasma. The ionised carrier gas is projected at high velocity beyond the end of the electrodes as a result of the high density electric fields, giving rise to the term 'plasma jet' or 'plasma plume'.

Depending on the energy source and the conditions under which the plasma is generated, the arc discharge itself can be between 5,000°C and 7,000°C (9,000°F to 12,600°F) and such a configuration is known as Thermal Plasma. Also, the presence of the charged gaseous species makes the plasma gas highly reactive and is the reason why plasmas are referred to as the 4th state of matter: the charge that particles carry makes their behaviour significantly different from other gases, solids or liquids. Only thermal plasmas are of significance in waste degradation and therefore the rest of our discussion in this review will be focussed on this class of plasma technology.

Figure 2-23: Illustration of the operation of a plasma torch



Source: Westinghouse

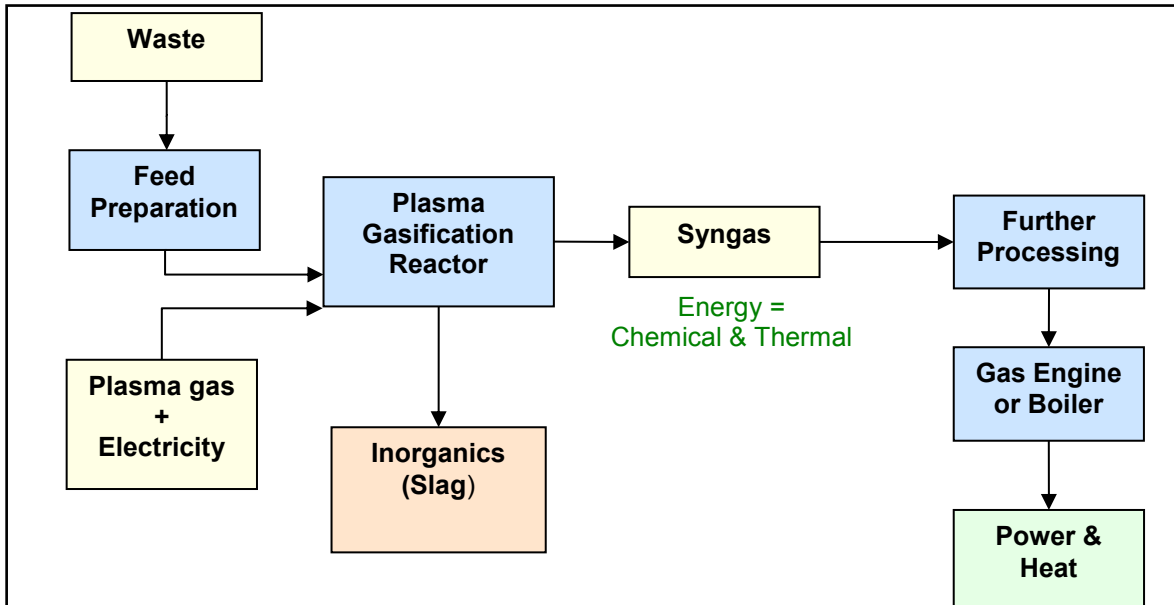
Plasma gasification uses extremely high temperatures in an oxygen starved environment to decompose organic waste materials into basic molecules. The extreme heat and lack of oxygen results in pyrolysis and

⁹ High temperature processing of wastes melts the inorganic components, resulting in a glass-like material (vitrified slag), which is much more stable than the ash which results from lower temperature processes. The slag also immobilises any non-volatile metals that were in the input waste.

¹⁰ The electrical discharge for plasma generation can be provided by DC (direct current) or AC (alternating current) sources.

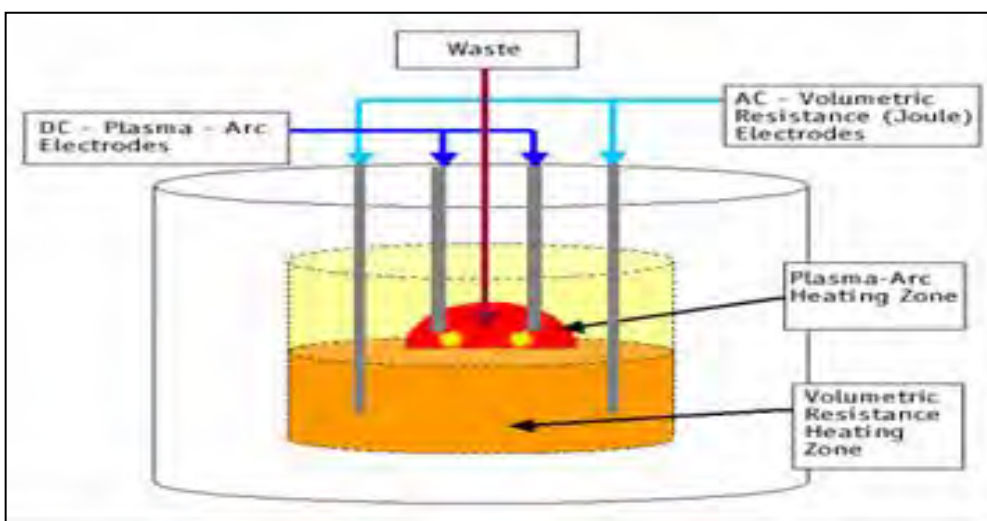
gasification reactions taking place, which convert the waste into syngas. The heat source is plasma gas, which is generated by the input of electrical energy to a gas (usually air). The plasma gas is the hottest, sustainable heat source available attaining temperatures between 3,000 and 8,000°C.

Figure 2-24: Schematic of a Plasma Gasification Process



Thermal plasmas are further subdivided into two categories – ‘transferred’ and ‘non-transferred’ types. These refer to the way in which the electric discharge is produced. In ‘non-transferred’ plasma, both electrodes (cathode and anode) used to produce the high energy electric discharge are part of the plasma torch assembly. The torch therefore has the sole function of producing hot plasma gases. In ‘transferred’ plasma systems, the electricity discharge occurs between the plasma torch (the cathode) and the conductive lining of the reactor wall (the anode) or in some cases a metal bath. Thus in this case the reaction vessel is itself part of plasma generation. Some developers use graphite electrodes inserted into the waste reactor instead of a plasma torch assembly to produce a transferred arc (see, for example, Figure 2-14). In these systems the arc occurs between the inserted electrode and the container walls or the molten metal pool at the bottom of the reactor. This type of plasma system is not as widely used as the plasma torch arrangement for waste applications.

Figure 2-25: Plasma generation using graphite electrodes



Source: InEnTec

The importance of transferred and non-transferred arc types of plasma processes is often downplayed because many developers indicate that they can operate their technologies in both modes. But the way in which the plasma system is designed to degrade waste, has significant knock-on impacts on many aspects of the process that include:

- the efficiency of waste destruction;
- tar formation;
- dust carryover;
- gas phase destruction efficiencies.

Thus, for example, a process configuration in which the plasma torches are used to provide heat to only a part of the waste reactor will experience issues similar to many other types of combustion or starved-air processes. Better heat transfer will be possible in those configurations where the waste is in direct contact with the plasma arc, and feed preparation might be less critical, but the reactor construction and electrode life-span are likely to be critical because of the potentially higher reactor wall temperatures and the fact that the graphite electrodes are directly exposed to the reactor conditions and are 'consumed' in the process.

Therefore, while switching between transferred and non-transferred modes of operation might be relatively straightforward in some applications of plasma (such as welding) this would not be the case when processing solid waste. Some of our reservations stem from our knowledge of other high temperature waste treatment processes such as slagging gasification, where the particularities of treating heterogeneous waste at high temperatures could result in issues of note, such as refractory instability (the temperature at the wall of plasma vessels is reported to be usually about 1650°C). To overcome this, expensive refractory has had to be utilised coupled with careful reactor design to minimise refractory damage. In addition, the reactor will have to be designed so as to be an effective anode without being adversely affected by the high temperatures experienced when in direct contact with the plasma arc.

Plasma gasification is carried out under oxygen depleted conditions, which results in the production of syngas, a vitrified slag and molten metal, the proportions and composition of which will depend on the composition of the input waste. The main driver in the development of this type of process is the opportunity to recover gases rich in chemical energy that can be utilised in high efficiency energy recovery systems or used as a chemical feedstock. Also, because the process involves less air and can result in lower volumes of off-gases, it is seen by many developers as suitable for applications in which space is at a premium (e.g. onboard ships). The smaller flue gas volumes also bring benefits in terms of the scale of downstream air pollution control equipment; though this does not necessarily translate into a reduced complexity or lower cost. Emissions of pollutants such as nitrogen oxides (NO_x) and sulphur dioxide (SO₂) are avoided, but other reducing contaminants such as H₂S (hydrogen sulphide), NH₃ (ammonia) and COS (carbonyl sulphide) may have to be abated. Some trace contaminants can require more sophisticated and potentially more expensive counter-measures than would be necessary with conventional incineration.

Syngas Cleaning Requirements

Gasification processes, including high temperature slagging and plasma gasification processes, will produce a 'raw' syngas that contains several contaminants such as: dust, HCl, H₂S, tar droplets, NH₃, COS, heavy metal species and alkali metal salts. Table 2-8 considers the technical challenges faced when cleaning syngas for downstream high efficiency power recovery systems and the potential mitigation measures. Numerous process developers are striving to utilise higher efficiency energy recovery systems, such as gas engines and gas turbines and ultimately fuel cells. For these devices the syngas must be cleaned to varying degrees to remove the majority of contaminants.

Table 2-8: Technical challenges for syngas cleaning

| Contaminant | Technical challenges |
|---------------------|--|
| Dust (particulates) | Solid phase materials entrained in the raw syngas exiting from the gasification reactor. Typically includes inorganic “ash” derived from mineral matter in the feed material and carbon dust produced as a solid from the thermodynamic reactions where carbon is rejected to the solid phase. Particulates can be removed from the syngas by various filtration technologies: cyclone filters; barrier filters (ceramic candle, bag and packed bed filters); ESP's ¹¹ and wet scrubbers. |
| Tar droplets | As the syngas cools downstream of the reactor, vaporised tars will condense either onto cool surfaces and/or into aerosols or small droplets. As well as potential blocking of pipework, tar removal is critical in systems where the syngas is compressed prior to use, such as gas turbines. Wet scrubbers and WESP's ¹² have been used widely in the removal of tars from gas streams in coal and coke processing plants and in Japanese slagging waste gasification plants integrated with gas engines. Catalytic tar destruction techniques are also being developed, which retain the energy value of the tar compounds in the syngas. |
| Halogen compounds | As in combustion plants, if the incoming waste contains materials incorporating halogen compounds (chlorine, fluorine and bromine) then acid halides (HCl, HF and HBr/Br ₂) will be present in the syngas. These compounds are extremely corrosive and should be removed to protect downstream equipment made from steel. This can be achieved by wet scrubbing techniques or dry absorption with lime or bicarbonate sorbents. |
| Sulphur compounds | In a combustion unit sulphur compounds are converted to sulphur dioxide (SO ₂) which need to be removed to protect downstream equipment made from steel. The presence of SO ₂ also limits the exit temperature from a waste heat recovery boiler to avoid condensation of SO ₂ as sulphuric acid. In a gasification environment, because of the reducing rather than oxidative conditions, sulphur present in the waste is converted primarily to hydrogen sulphide (H ₂ S) and other trace compounds, such as carbonyl sulphide and di-sulphide (COS and CS ₂). |
| Nitrogen compounds | A typical waste combustion process will produce significant levels of NOx (nitrogen oxides) formed from reactions involving the nitrogen from the combustion air which is added to the process in an excess of the stoichiometric requirement ¹³ and nitrogen molecules within compounds entering as part of the waste. In the reducing environment of a gasifier, nitrogen contained within compounds in the waste will be converted to ammonia (NH ₃) and hydrogen cyanide (HCN). When combusted in downstream equipment these compounds will be converted into NOx, which would need to be removed catalytically in order to meet local air emission limits. |

¹¹ Electrostatic Precipitators

¹² Wet Electrostatic Precipitators

¹³ more than the stoichiometric quantity of air (oxygen) required to meet the chemical reactions to convert the carbon and hydrogen completely into carbon dioxide and water

| Contaminant | Technical challenges |
|---------------------|---|
| Heavy metal species | <p>Volatile and semi-volatile heavy metals are present in MSW in trace concentrations. In a combustor or gasifier the less volatile metals, such as chromium (Cr) and zinc (Zn) will remain in the solid phase (ash or slag) whilst the more volatile elements, such as mercury (Hg), cadmium (Cd), arsenic(As) and lead (Pb), will leave in the syngas in either elemental form or as other compounds, such as chlorides and sulphides. Typically, heavy metals can be found in the following waste materials¹⁴.</p> <p>Hg – batteries, plastics (PVC), fungicides, medicines, paints, fluorescent tubes, electronics</p> <p>Cd – plastic stabilisers, papers, paints, pigments, batteries, inks, textiles, glazed ceramics</p> <p>As – clay materials, paints, medicines, pesticides, cosmetics, leather, electronics, glass</p> <p>Cr – cardboard, paper, paints, leather, glass, plastics, fireproofing, pigments</p> <p>Zn – printing inks, paper, rubber, plastics, batteries, pesticides, pigments, electronics</p> <p>Pb – plastics, paints, pigments, paper, cardboard, rubber, cables, galvanized items. electronics</p> <p>Metal carbonyl species can also form in a reducing environment in the form of sub-micron particulates or aerosols and will need to be removed from the syngas.</p> |
| Alkali metal salts | <p>Typically, mineral matter contains high levels of alkali metal salts, particularly sodium, potassium and magnesium as the moisture content of the waste will contain such inorganic minerals. Above 800°C, a typical operating temperature in large scale gasification systems, the alkali salts can become molten or vaporise which creates problems from deposition on cooler downstream surfaces. These alkali vapours condense to form small particulates (< 5µm) or aerosols combined with the soft, 'sticky' alkali metal salt particles and are difficult to remove. In power generation applications, the alkali salts could re-vaporise at the high operating temperatures prevailing. R&D scale experiments have shown that high temperature removal of alkali metal salts is possible using ceramic filters and packed bed filters employing activated bauxite.</p> |

Source: WSP analysis

Cleaning the syngas allows the chemical energy (ca. 80% of the energy value of the input waste) to be conserved and used more efficiently and more flexibly. The syngas volume is much smaller and therefore the cleaning plant is smaller and requires a smaller footprint.

The particulate loading for fixed bed gasifiers (updraft and downdraft) can range between 0.1 – 1.0 g/Nm³ and the tar loading from 0.1 – 100 g/Nm³. For fluidised bed gasifiers (bubbling and circulating) the ranges reported are 2 – 35 g/Nm³ for fixed bed and 1 – 15 g/Nm³ for fluidised beds. These ranges are quite wide and the contaminant loadings significant presenting a difficult technical challenge.

¹⁴ Source: adapted from Vassilev & Braekman-Danheux, Fuel Processing Technology, 59 (1999), 133-161

The electrical conversion of the produced syngas via spark-ignition gas engines requires the syngas to be cleaned to a high quality of cleanliness and for gas turbines and fuel cells the quality of the syngas needs to be extremely clean. Table 2-9 summarises published data, which indicates the syngas cleaning requirements in order to utilise it in various energy generation equipment.

Table 2-9: Required syngas quality for various energy generation systems

| Contaminant | Quality specification for | | | |
|---|--|--|---|---------------------------|
| | Direct combustion | Gas engines | Gas turbines | Fuel cells |
| Particulates (dust) | Removal of material >10µm | < 5 mg/Nm ³ | < 1.2 mg/Nm ³ for particulates of 10-20µm | < 0.02 mg/Nm ³ |
| Tars¹⁵ | No removal required but temperature must be maintained to avoid tar condensation | < 30 mg/Nm ³ | < 5mg/Nm ³ | < 0.1 mg/Nm ³ |
| Halogen compounds | Will be removed in downstream gas cleaning devices | < 10 mg/Nm ³ | < 1mg/Nm ³ | N/A |
| Sulphur compounds | Will be removed in downstream gas cleaning devices | < 100 mg/Nm ³ | < 1.5 mg/Nm ³ | N/A |
| Nitrogen compounds | Downstream emissions must meet local regulations | NH ₃ removal important to minimise NOx formation, typically < 50 mg/Nm ³ | NH ₃ removal important to minimise NOx formation | NLDA |
| Heavy metal species | Downstream emissions must meet local regulations | NLDA | < 1ppm | NLDA |
| Alkali compounds | No removal required | < 1 mg/Nm ³ | < 0.1 – 0.2 mg/Nm ³ | N/A |
| N/A = None Allowed; NLDA = No Literature Data Available | | | | |

Source: Various

Clearly, it can be seen that more stringent syngas cleaning is required from direct combustion to fuel cell applications where virtually no contamination can be tolerated.

Capex and Opex Indicators for Gasification and Pyrolysis Processes

There is little real cost data available for gasification and pyrolysis processes primarily because there are very few operating facilities with sufficient operational track record to provide meaningful data. Of course, the 122 operating plants in Japan could provide an indicator but this information is almost impossible to obtain and it cannot be compared with other geographical markets because the drivers in Japan forcing the acceptance of gasification as a waste treatment technology with slagging of the inorganic content of the waste to produce recyclable products is not mirrored in any other country. Consequently, no cost data for gasification and pyrolysis processes is included in this report.

¹⁵ in the particular case of gas turbines where compression of the syngas to elevated pressure is required it is essential to remove tars to very low levels to ensure that condensation does not occur in the compression stage

List of Case Studies Included

The following reference plants have been selected for the Case Studies and the key reason for inclusion is shown in blue bold:

Table 2-10: Case Studies and Reasons for Inclusion

| | Plant name | Country | Why included |
|----|----------------------------|-----------------|---|
| 1 | AEB, Amsterdam | The Netherlands | The largest plant in the Netherlands. The most recent two lines added to the original four line facility employs a reheat Rankine steam cycle and produces electricity with a total thermal efficiency of 30% . |
| 2 | Lakeside, London | UK | A recently commissioned merchant incinerator developed by a major UK waste management company and located near to Heathrow Airport. The plant processes residual MSW and C&I waste and is the only plant supplied to date by a Japanese supplier. |
| 3 | Spittelau, Vienna | Austria | This is a relatively old conventional moving grate combustion plant. However, it was the first facility that used architectural treatment to gain public acceptance . |
| 4 | Allington, Kent | UK | One of the largest fluidised bed MSW incineration plants in the world . The plant was supplied by Lurgi Lentjes with technology licensed from the Ebara Corporation of Japan. Ebara has supplied more than 100 such plants in Japan. |
| 5 | Issy les Moulineaux, Paris | France | The newest and largest incineration plant in France. The plant is built on the side of the River Seine in the centre of Paris and the building only has a vertical profile of 27 metres as 30 metres of the plant is below ground. The roof is flat and covered with grass and shrubs and the exhaust stacks only protrude 5 metres above the building roofline. |
| 6 | Reno Nord, Aalborg | Denmark | Modern incinerator in CHP mode and providing district heating to the local city . |
| 7 | Sarpsborg II | Norway | The newest gasification plant using the Energos two stage gasification/combustion process. |
| 8 | Bilbao | Spain | High efficiency plant linked to an adjacent combined cycle plant. The steam from the combustion plant is passed to the adjacent power plant and converted to electricity at higher efficiency. |
| 9 | Riverside, London | UK | The newest and largest combustion plant in the UK using state-of-the-art grate combustion technology and high steam pressure and temperature . The majority of the MSW is delivered to the site by barge via the River Thames. |
| 10 | Brescia | Italy | New plant in Italy operating with high thermal efficiency . |

| | Plant name | Country | Why included |
|----|-----------------------------|---------|--|
| 11 | Mainz | Germany | The new third line installed at this existing combustion facility operates with high efficiency due to integration with and adjacent gas turbine plant. |
| 12 | Lahti II | Finland | Metso Power has supplied many fluidised bed combustion plants via companies it has acquired over the years – Tampella Power, Gotaverken Miljo and Kvaerner. The company has developed a CFB gasification plant for RDF fuels that is operating in Finland. This plant has been included as a Case Study because it is the first large scale commercial gasification plant supplied by a large well capitalised company. |
| 13 | Montgomery County, Maryland | USA | Relatively old plant refurbished with the newest Martin grate and the LN deNOx technology . |
| 14 | Slagging Gasification | Japan | A review of slagging gasification in Japan . There are currently 122 operating slagging gasifiers processing MSW with more under construction. This review describes the processes supplied by the leading Japanese companies. |
| 15 | Plasma Gasification | Various | A worldwide status review of plasma gasification technologies currently being marketed and close to commercialisation. |

Case Study 1 – AEB, Amsterdam, The Netherlands

Overview

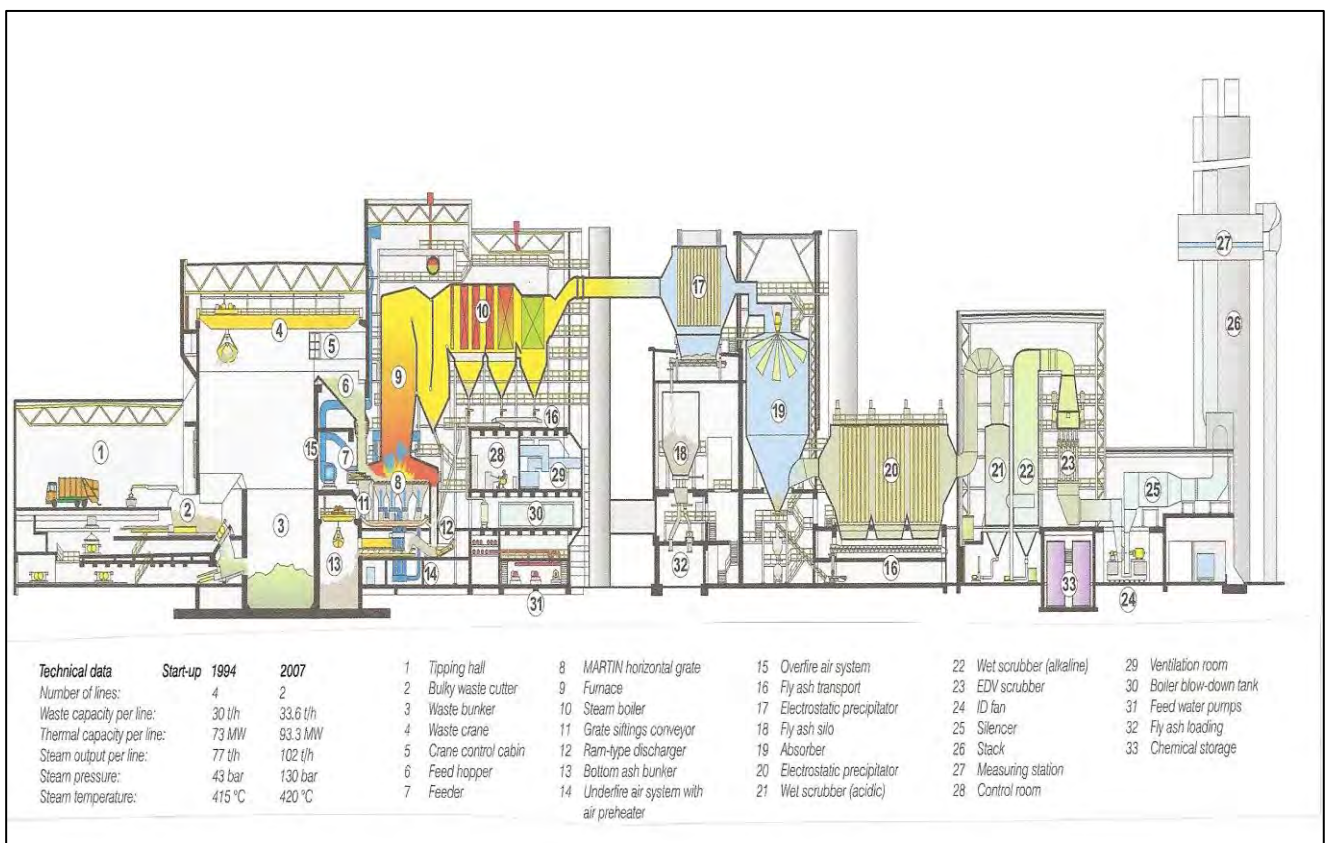
The original Afval Energie Bedrijf (AEB) plant was built in Amsterdam in 1969 with four combustion lines supplied by Widmer & Enrst (W&E). The plant underwent its first refurbishment and upgrading of the air pollution control systems by Lurgi in 1993. Two new state-of-the-art lines were added in 2007 and the performance of the steam cycle for the new two lines is optimised by including a reheat cycle.

The plant now comprises six incineration lines and processes all of the household, industrial and commercial waste from Amsterdam and 27 neighbouring municipalities amounting to 1,370,000 tonnes each year. The plant produces electricity for export to the grid a small amount of heat energy exported to the local district heating network.

The plant is one of the largest Waste-to-Energy plants in the world and the focus of the newest two lines is to maximise the recovery of both energy and re-usable resources.

The Process

Figure 2-1-1: Schematic of the moving grate process at Amsterdam



Source: Martin GmbH

Waste reception, storage and feeding

In the delivery area, newly arrived waste is weighed, logged into the computer system and tipped into the storage bunker. The crane operators continually mix the waste in the bunker in order to homogenise the types of waste (high CV/low CV) and moisture content. The bunker is designed to hold sufficient fuel for several days of feed as waste is only delivered during the day and on working days but the plant operates for 24 hours per day.

The tipping hall and bunker are housed within closed buildings to prevent dust and odours from escaping into the environment. In addition, air is continually extracted from the pit to maintain a negative pressure. The extracted air serves as combustion air for the combustion system. The facility also operates a bulky waste shredder.

The manually operated crane system lifts the waste from the bunker and transports it to the feed chute, which consists of a hopper and chute. The feed rams push the waste from the feed chute onto the combustion grate. Due to the height of the waste column in the chute, air is unable to leak into the combustion system. Microwave level detectors report the height of the waste column in the chute to the crane operator. Bridging and obstructions are prevented by the inclined side walls of the hopper and the flaring of the chute. A shut-off damper located underneath the feed hopper is closed when the plant is not operating.

The feed ram changes the direction of waste flow from vertical to horizontal. The waste, compacted in the feed chute, is loosened during this process and pushed onto the grate in amounts determined by the combustion control system. Each feed ram is driven by a hydraulic cylinder. The combustion control system prescribes the cycle time, stroke length and stroke speed to achieve uniform combustion on the grate.

Combustion

The original four line plant uses W&E horizontal grates. The two new lines employ Martin horizontal grates, which is the same technology having been acquired by Martin. The grates consist of alternating rows of fixed and moving grate bars. Neighbouring moving grate bar rows make a counter movement, thus effectively transporting and mixing the waste to ensure good burnout.

The horizontal grate is of modular design. The length of each module is fixed but the width may vary depending on the design. Each module has its own drive and supply of underfire air, both of which can be controlled separately. A typical grate configuration consists of 3 modules in the waste flow direction.

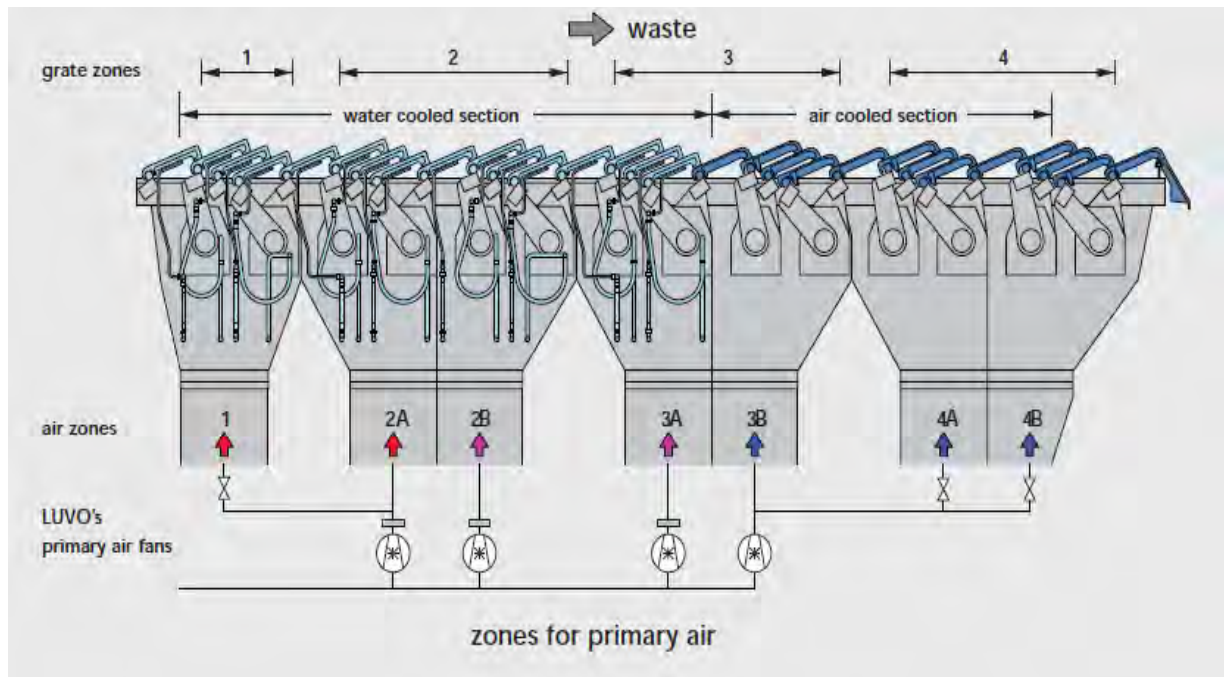
Figure 2-1-2: The horizontal grate system employed at Amsterdam



Source: Martin GmbH

The hoppers that feed both incineration lines are filled by the waste cranes. The waste drops through a water-cooled intake shaft onto the dosing ram. The waste is burned on horizontal grates that are identical to the existing ones but are partially water-cooled. The grate is of the double-motion overthrust type (W&E design) and comprises three parallel runs, each with seven air zones.

Figure 2-1-3: Schematic of the grate bar design



Source: AEB

The grate cooling system is connected to the water-steam cycle so as to use this heat too. The cooling pipes are cast into the grate bars and the connection between the grate bars consists of fixed pipes with flexible tubes on the extremities only that connect to the hot water circuit. The first half of the grate surface is cooled in order to counteract burning of the grate bars and to enable incineration of high-calorific industrial waste. The biggest advantage of water cooling is that it reduces wear on the grate bars, which increases bar life. It also enables incineration with less excess air. Detailed reliability investigations have been carried out into the grate properties needed to guarantee two years' uninterrupted operation.

The bottom ash produced during waste incineration drops down the slag shaft into a water-filled de-slagger. Each grate has three of these (one per grate run). Transport on to the slag bunker is by entirely enclosed oscillating conveyors. Water vapour is sucked out of the de-slagging system by the tertiary air exhaust system.

- Achieving maximum efficiency means having as little excess air as possible. To combine this with efficient waste incineration and obtain thoroughly burnt flue-gas and bottom ash, the air is injected in stages:
- Primary combustion air is blown in from under the grate and the bottom layer of waste. Every zone can be independently heated to the desired temperature. Pressure and air amount can be individually adjusted for each section (bank/zone).
- Flue gas that has passed through the bag filter is re-circulated as secondary air. Large nozzles are used to make sure that the flue gas is thoroughly mixed. This results in a lower temperature and a more even profile. The combination of low-oxygen flue gases reduces the production of nitrogen oxides.
- Tertiary air provides a second mix, this time with oxygen from the air, so that good combustion is possible with only 6% oxygen.

The air injection has been designed using CFD (Computational Fluid Dynamics) in order to guarantee the optimum turbulence in the combustion zone and a stable, even flue gas flow in the boiler.

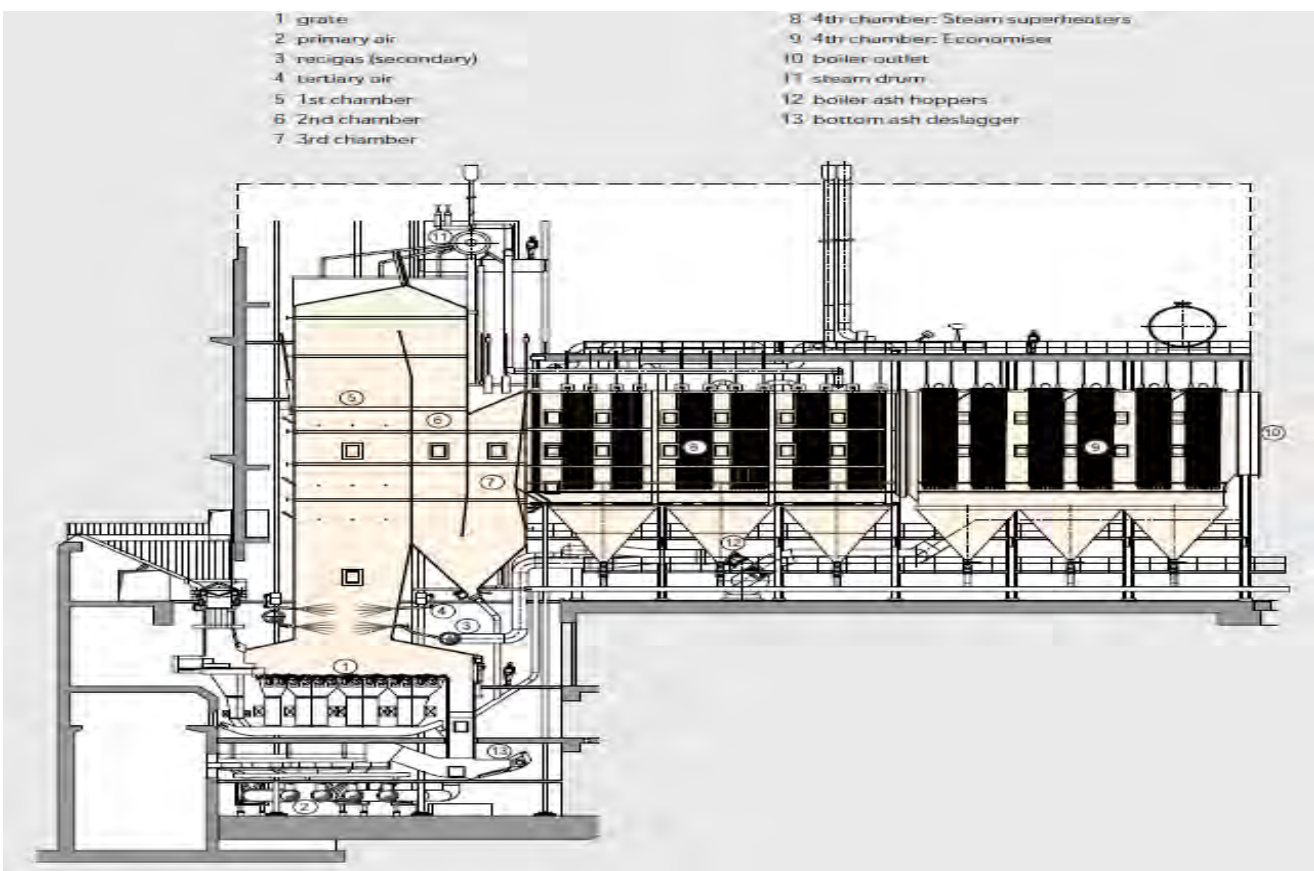
Energy Production

The high efficiency boiler has three empty radiation chambers and a horizontal convection section with tube banks for the steam superheaters and economisers (ECOs). To achieve the maximum possible reliability and capacity margin, the furnace is spacious with large heat-exchange surfaces. The designed velocity of the flue gas is also low, as is the temperature of the flue gas before it reaches the first steam superheater banks. This becomes very clear when one compares the size of the first radiation chambers with those of the existing Waste-to-Energy Plant. The greater volume helps reduce the amount of dust in the flue gas and also lowers the temperature. It also increases the reliability of the steam superheater banks and the economisers. The spare capacity also contributes to the flexibility needed to separately generate saturated steam for the intermediary superheating.

The first and second boiler radiation chambers are fitted with Inconel cladding, as too are the membrane walls under the brickwork. One of the reasons for this is that, because of the high pressure, the temperature of the membrane walls reaches some 340°C instead of the usual 270°C. It is possible to also fit cladding in the third boiler radiation chamber but whether this will be done depends on the amount of corrosion of the membrane walls in practice.

The boiler has been designed with an empty space between the superheater and economiser sections. This space can be used for an extra tube bank so as to achieve an even higher fresh-steam temperature of 480°C. This could further increase the WFPP's total efficiency in the future. With this in view, it is also possible to connect the superheater tube banks entirely for counterflow. The choice will depend on practical experience, in other words, the extent of damage to the tube banks. Only if the degree of wear through corrosion/erosion remains within practical limits higher steam temperatures will be used.

Figure 2-1-4: The Amsterdam boiler configuration

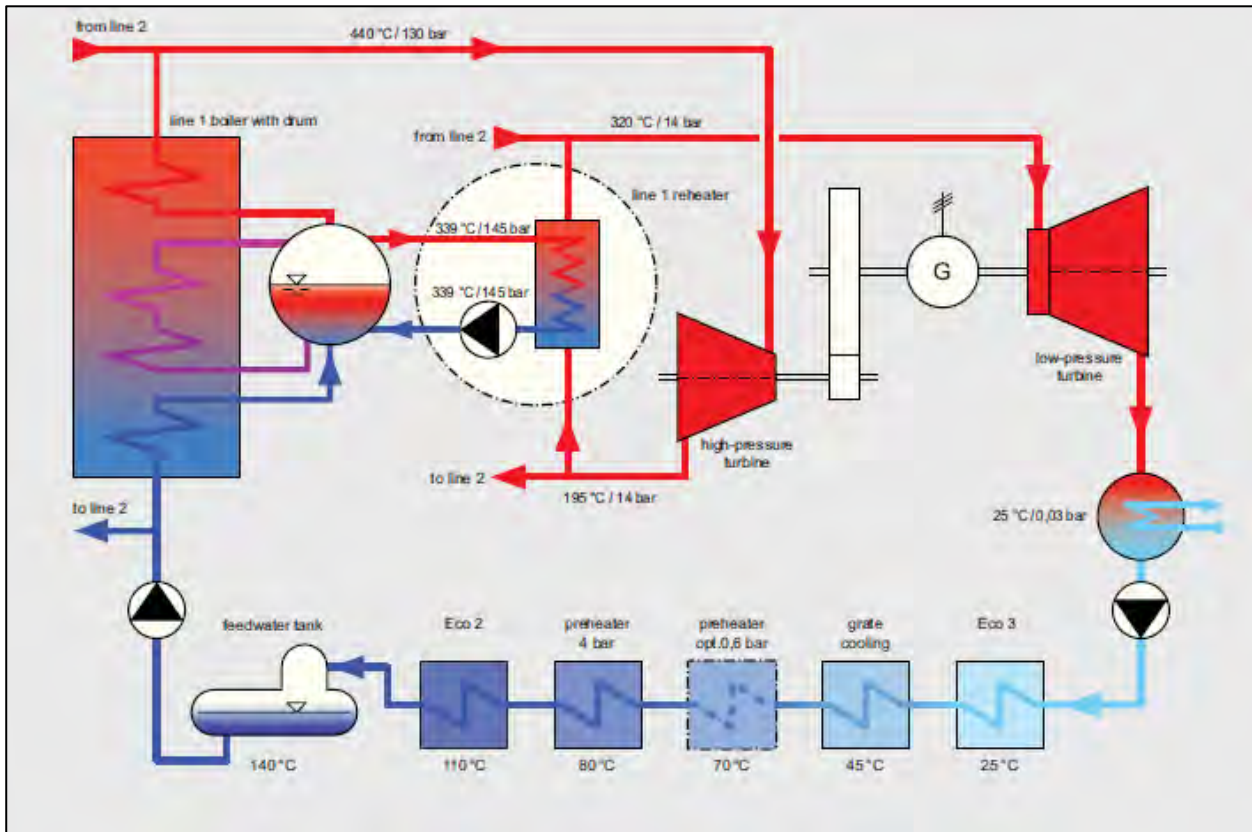


Source: AEB

The existing Waste-to-Energy plant has been optimised over the years and supplies electrical power with a net electrical efficiency of more than 22%. To achieve a net electrical efficiency of 30%, the amount of electricity generated per tonne of waste must be increased by more than a third. Thermodynamically, and experience from coal-fired plants, means the steam parameters (pressure and temperature) could be increased in order to increase the efficiency. However, in waste-to-energy plants, higher steam parameters are always accompanied by corrosion caused by the presence of chlorine and alkali metals in the flue gas and the increase in steam temperature drastically reduces the life of the superheater. This approach would not create an optimally available, efficient plant. Therefore the following measures were combined in order to achieve higher efficiency without additional risks:

- the original waste-to-energy plant has gained significant experience in treating critical heat surfaces in the boiler by lining with Inconel and corrosion has been controlled. This high-quality nickel-chrome alloy is the basis of a number of measures designed to increase efficiency and take the boiler and water-steam cycle to a higher level;
- a higher steam temperature in waste-to-energy plants is critical owing to the sharp increase in corrosion to the superheaters. In the new lines of the Amsterdam plant, a steam temperature of 440°C was used instead of the usual 400°C, with the option of raising this to 480°C in future and the boiler design was optimised to minimise corrosion and erosion;
- increasing the steam pressure makes a significant contribution to raising efficiency but this can only be achieved proportionally to the steam temperature because of the need to condense the steam in the low-pressure stage of the turbine. The pressure has been raised from 40 to 125 bar, which has been made possible by the following crucial modification:
 - reheating of the steam from the high-pressure stage of the turbine using saturated steam from the steam drum of the boiler. Intermediary superheating of the turbine steam is a process that is used in coal-fired power stations to achieve higher efficiency. This is achieved with a heat exchanger operating directly with the flue gas, which has a major disadvantage for a waste fired power plant. The flue gas temperature in the boiler would need to be raised so high that the risk of corrosion would increase strongly. The solution to this problem was achieved by using an external heat exchanger for reheating with saturated steam;
 - saturated steam from the steam drum is used to raise the temperature of the steam for the second stage turbine. Generating saturated steam in a waste fired boiler creates fewer problems than generating superheated steam.
- minimising the oxygen level in the combustion zone from the typical 8 – 11% to 6% as a result of flue gas recirculation. The volume of flue gas is therefore reduced by approximately 40% and the amount of heat lost via the stack is minimised;
- maximising the use of flue gas energy as follows:
 - the temperature of the flue gas on leaving the boiler is lowered in relation to the usual 200-240°C and is kept at a constant 180°C by enlarging the first stage economiser;
 - a corrosion-resistant heat exchanger is fitted before the first flue gas scrubber (the quench) in order to preheat the condensate;
 - in the last polishing scrubber, the flue gases are cooled until the water condenses. This heat is also used for preheating the condensate.
- minimising the steam pressure after the turbine. Reheating the turbine steam and cooling the condenser with harbour water makes it possible to have a very low steam pressure after the turbine, which enables maximum turbine efficiency.

Figure 2-1-5: The reheat steam cycle employed at Amsterdam



Source: AEB

Air Pollution Control

It was not the emission limits under Dutch law (Incineration of Waste Materials Act) that constituted the criteria for designing the flue gas cleaning system. Instead it was the excellent operating parameters of the existing Waste-to-Energy Plant. This raised the bar in relation to what was prescribed by law.

As in the existing plant, Selective Non-Catalytic Reduction (SNCR) is used for nitrogen oxide reduction. To help optimise efficiency, compressed air and not steam is used for injecting ammonia, diluted with softened water.

For the pre-separation of fly ash, an electrostatic precipitator has been fitted after the boiler outlet. Thanks to this filter, in combination with the boiler's two-way ash conveyance system, the maximum amount of fly ash can be reused.

A fabric filter has been fitted to remove fine particles. Fine powdered activated carbon or blast furnace coke is blown in as the adsorption medium for the filter. Powdered limestone is added to the coke injection to eliminate the risk of fire and explosions. It also forms a filtering layer on the filter bags. The coke adsorption medium separates out dioxins and furans right at the beginning of the flue gas cleaning process. Heavy metal content is also reduced to such an extent that products from the wet flue gas cleaning process can be reused.

The hydrochloric acid and sulphur dioxide scrubbers are the next stage in cleaning acid components and ammonia from the flue gases. The hydrochloric acid scrubber is a packed bed scrubber that captures the acid remaining in the flue gas after the quench. The spray from the hydrochloric acid scrubber is sent to the quench as a concentrated hydrochloric acid solution. The sulphur dioxide scrubber is an open scrubber in which lime-milk solution is added as a neutraliser. At pH 6, this scrubber captures sulphur dioxide that reacts in the scrubber to form a gypsum slurry. By using a fabric filter, relatively clean gypsum can be produced that is

suitable for reuse. A centrifuge separates the gypsum from the slurry as a dry product that is stored in a container for transport and reuse.

After the sulphur dioxide scrubber is a separate polishing scrubber that also functions as a heat exchanger. The scrubber consists of a packed bed over which water circulates that is cooled by a water-water heat exchanger. This cooling of the flue gas leads to condensation of the water in the flue gas, further reducing emissions. The recovered heat is used in the first stage for preheating the condensate. By super-cooling the flue gases, the polishing scrubber with ECO3 produces virtually pure condensation water that can be reused in the flue gas cleaning system, mainly in the hydrochloric acid scrubber and the quench.

Finally, the purified flue gas is kept at underpressure by an induced draught fan. This runs 'wet' in the saturated flue gases that pass through a drip tray and emissions monitoring equipment to the chimney stack.

Resource Recovery

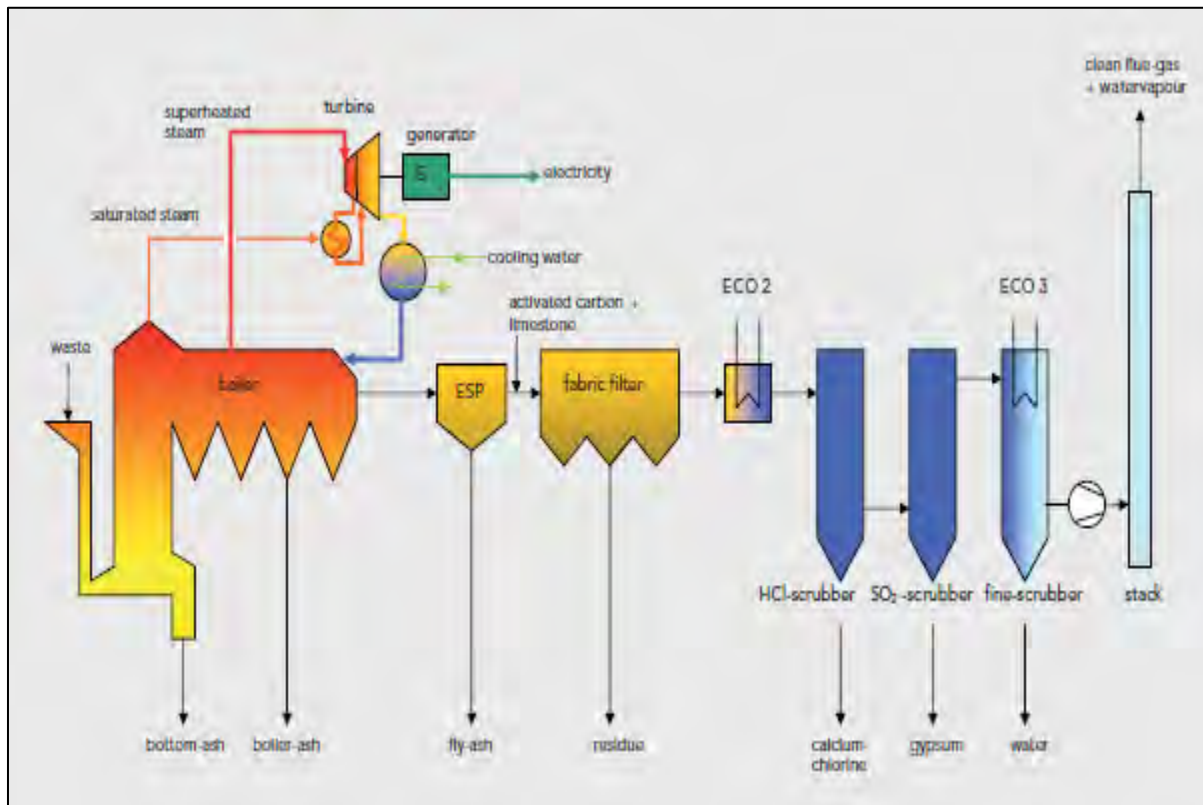
The innovative nature of the Amsterdam plant also recovers and recycles the various residual materials from the process:

- the bottom ash is processed in the slag reprocessing facility;
- boiler ash can be selected according to quality;
- fly ash is separated in the electrostatic precipitator;
- the chlorine (hydrochloric acid) is processed into calcium chloride in the salt recovery system;
- The sulphur (sulphur dioxide) is processed into gypsum;

Only the residual materials from the fabric filter (hazardous waste) will still have to be disposed of in a hazardous landfill for the time being.

The blowdown from the quench and hydrochloric acid scrubber is neutralised with limestone (CaCO_3). The pH is increased further by the addition of calcium hydroxide (Ca(OH)_2) and caustic soda (NaOH). The addition of hydrogen sulphide (H_2S) produces a precipitation of heavy metals as sulphides. This slurry is separated and transported to the filter press. An evaporation plant strips any ammonia from the solution and recycles it for ammonia injection in the boiler (SNCR). A sand filter, ion exchanger and active carbon filter together constitute the polishing stage that guarantees the quality of the salt, which can be marketed as a product.

Figure 2-1-6: The flue gas cleaning and product recovery process at Amsterdam



Source: AEB

Ash Handling and Processing

Bottom ash: after incineration, the inert material remains behind in the form of bottom ash. This bottom ash is processed in the slag reprocessing facility and must conform to the Dutch Building Materials Order. The Amsterdam plant is focussing on the highest quality use of bottom ash. Various techniques can be used to reclaim ferrous and non-ferrous metals. Using a wet process, clean sand and grit are produced that can be used for producing sand-lime bricks and concrete.

Boiler ash: depending on the temperature, the properties of the boiler ash during flue gas cleaning in the boiler will differ. For the ash collected in the hoppers under the superheaters and the economiser, the operators can decide whether the contents of each hopper should be processed as fly ash or bottom ash.

Fly ash: for environmental reasons, an electrostatic filter for pre-separation of fly ash before the fabric filter was used. In terms of process technology, this is unnecessary but the fly ash is kept apart from the flue gas cleaning residue separated in the fabric filter, which produces a “better” product that can be recycled more easily. This enables its use in asphalt concrete and avoids disposal to landfill.

Salt: the acids in the flue gases in the quench and in the hydrochloric acid scrubber react with limestone (CaCO_3) to make a calcium salt solution. A brine plant has been built that cleans the polluted salts and evaporates them to produce a clean solution for re-use in applications such as salt for roads or for use in the chemical industry.

Gypsum: the gypsum produced in flue gas cleaning plant is comparable with gypsum from coal-fired power stations. It can be used in the production of building materials, plaster blocks and plasterboard walls.

Plant Performance

MSW Processed

The Amsterdam plant consists of two incineration lines, each with a thermal capacity of 93.3 MW. At an average calorific value of 10MJ/kg, this corresponds to a nominal throughput of 33.6 tonnes/hr of waste, or a total of 1,600 tonnes/day. Compared with other waste-to-energy plants, these are very large units. For waste incineration, their size has the major advantage that fluctuations in the waste processed can be easily absorbed. Variations in the composition of the waste have less effect and the boilers can operate steadily and without disruptions.

Power and Heat Generation

The two boilers are designed to produce a thermal output of 93.6 MW and produce steam at 130 bar and 440°C with a thermal efficiency of 87.14%.

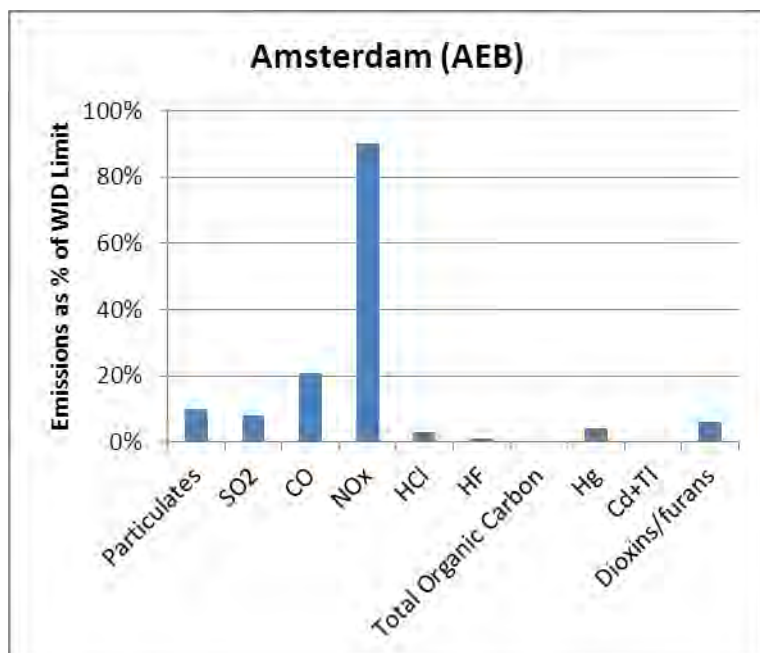
One steam turbine and generator is shared between the two lines to take the total steam flow and produce 66 MW_e. The electrical conversion efficiency during the Acceptance Test was 30.6%.

Environmental Performance

Emissions to Air

The emissions to air must meet the EU WID limits. Typical measured values are presented below:

Figure 2-1-7: Emission performance at Amsterdam



Source: interpreted from AEB data (circa Feb 2011)

Emissions to Water

The plant produces no waste water. All water produced is internally recycled for use in other process steps or evaporated.

Emissions to Land

Fly ash from that bag filter and heavy metal containing filter cake from the gas cleaning process are disposed of the hazardous landfill.

Footprint and Visual Impact

It can be seen from the photograph below that the Amsterdam plant looks like a typical waste-to-energy plant and has no special architectural treatment, although it should be noted that the original plant has been in operation for many years and the new two line extension is operating with a high efficiency.

Figure 2-1-8: The Amsterdam Waste-to-Energy plant



Source: presentation given by A.A.M. de Waart

Operability, Reliability and Availability

The Amsterdam plant has operated satisfactorily over the past few years and achieved a high availability. High availability is a primary requirement for operating a waste-to-energy plant profitably. Most of all, it is unscheduled shutdowns that lead to high costs and a reduction in income. In order to optimise the availability of the WFPP in spite of its innovative character, the following measures were taken, among others:

- The entire first and second boiler radiation chambers will be protected with a high-quality nickel alloy (Inconel cladding);
- In the event of wear, every superheater set can be replaced within 72 hours;
- All components are built for uninterrupted operation (journey time) of 24 months instead of the usual 12 months. This means that they can operate for two years between major servicing. Thanks to these measures, the duration of this scheduled servicing work has been shortened from 21 days to 14 days;
- Systematic analyses to identify shortcomings in safety and operational reliability, allowing improvement measures to be taken at an early stage;
- They have resulted in a large number of detailed optimisations that have been included in the engineering. Making a special effort to involve AEB employees in all the design work has guaranteed that experiences with the existing plant have been included in the plans and that possibilities for optimisation have been exploited to the full.

The overall availability of the new two line plant reported by the operator is >90%.

Economics

The investment cost for the Amsterdam plant was in the order of € 370 million. The depreciation period was set at 15 years and the life of the plant was 20 years.

The project was financed entirely by debt. An amount of € 80 million was provided through “green” financing and the European Investment Bank (EIB) provided a credit facility of € 170 million.

Because of the environmentally friendly and innovative nature of the project, various European subsidies were provided:

- an EU 5th Framework programme subsidy was obtained on a number of elements of the design that differentiate the project from a traditional waste-to-energy plant;
- over a period of 10 years, the so-called MEP (Environmental Effectiveness of Energy Production) scheme provided a contribution per kWh to further stimulate the generation of sustainable energy from waste;
- because of the ‘green status’, financing at lower interest was possible;
- the CO₂ reduction plan of the Province of Noord-Holland also made a contribution.

The newest two lines of the Amsterdam moving grate combustion plant really is a state-of-the-art design. Not only does the process produce electricity at an efficiency of >30% but the plant also maximises recovery of materials for re-use in society, such as bottom ash and fly ash, as well as producing calcium chloride and gypsum as secondary by-products of the flue gas cleaning process. The annual availability is reported to be >90%.

Case Study 2 – Lakeside, London, UK

Overview

The Lakeside waste-to-energy facility was built under a joint venture agreement between Viridor and Grundon Waste Management and commenced operation in 2010. Using advanced technology, the award winning £160 million plant is capable of recovering energy from over 410,000 tonnes of residual waste per year from local authorities and business.

In an attempt to reduce amenity impacts to the local community and reduce any possible generation of vortices (which might interfere with the aircraft approach route to Heathrow airport), a series of architectural treatments for the building profile have been employed, including use of a curved roof, which reduces sharp edges and a novel configuration applied to the 75m stack.

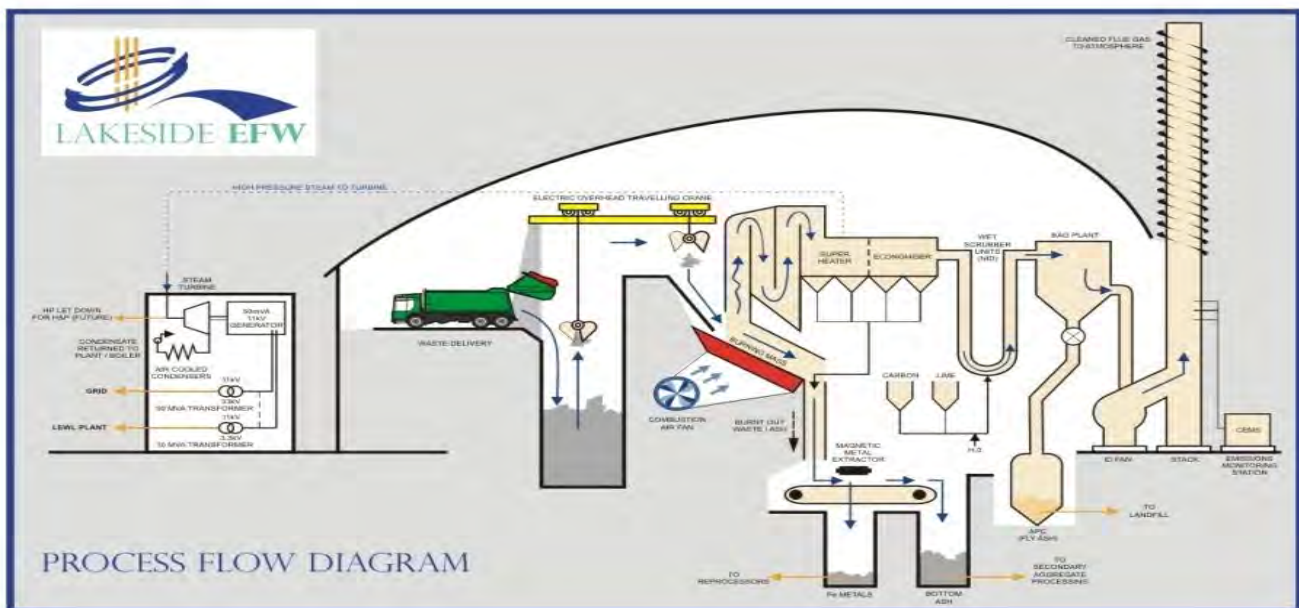
The facility generates 37MW of electricity the vast majority of which is exported to the National Grid, enough to meet the domestic needs of approximately 50,000 homes. Lakeside also has the potential to supply surplus heat to local infrastructure, meaning it could operate as a Combined Heat and Power (CHP) plant in future. The design life of the plant is 25 years.

The key outputs are approximated as follows:

- 250,000 MWh of electricity annually to the national grid;
- 20,000 tonnes of scrap iron;
- 100,000 tonnes of bottom ash, and
- 10,000 tonnes Air Pollution Control residues.

The Process Flow

Figure 2-2-1: Schematic representation of the process flow diagram for Lakeside



Source: <http://www.lakesideefw.co.uk/efw-guide.html>

The technology was supplied by Takuma of Japan who has supplied many waste-to-energy combustion plants in their home market.

Waste Reception, Storage and Feeding

Household and commercial/industrial residual wastes are delivered to the Lakeside facility by refuse collection, skip and articulated vehicles. The delivery vehicles are weighed on entry into the site, after which they discharge their load into a 7,500 tonne capacity bunker. The plant won an award for the bunker which was one of the biggest and most complicated continuous concrete pours in Europe. The empty vehicles are weighed again on exit to calculate the amount of waste delivered to the site. The bunker was designed to accommodate sufficient capacity for 4 days waste supply. Grab cranes positioned above the bunker mix the waste to obtain a more controlled calorific value before feeding it into a loading hopper from where it is pushed into the incinerator by hydraulic rams at a controlled rate.

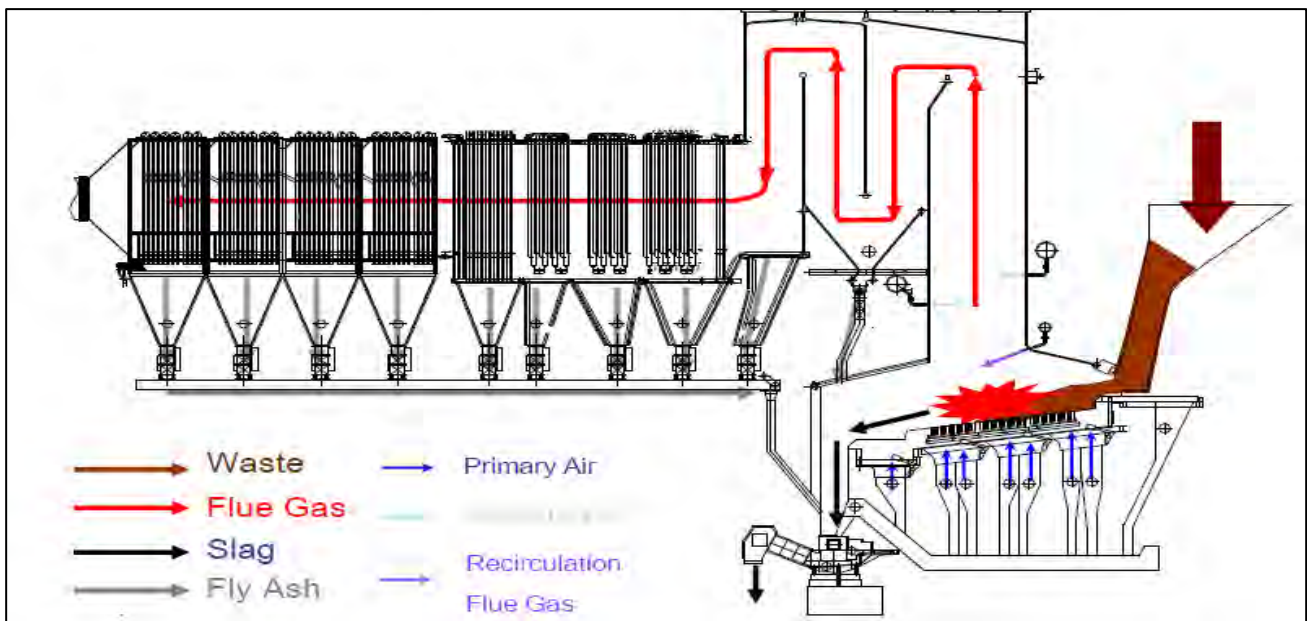
Combustion air is drawn from above the bunker in order to keep the tipping hall under slight negative pressure and obviate the release of odour.

Combustion

The hot gases produced by the incineration process are used to heat water in a boiler until it becomes superheated, dry steam at circa 45 bar pressure and 400 °C.

The Lakeside facility has two incineration lines each capable of a throughput of 27 tonnes of waste per hour. Each stream will produce approximately 7 tonnes of bottom ash per hour, of which 1.5 tonnes will be metal.

Figure 2-2-2: Combustor and horizontal boiler layout for Lakeside



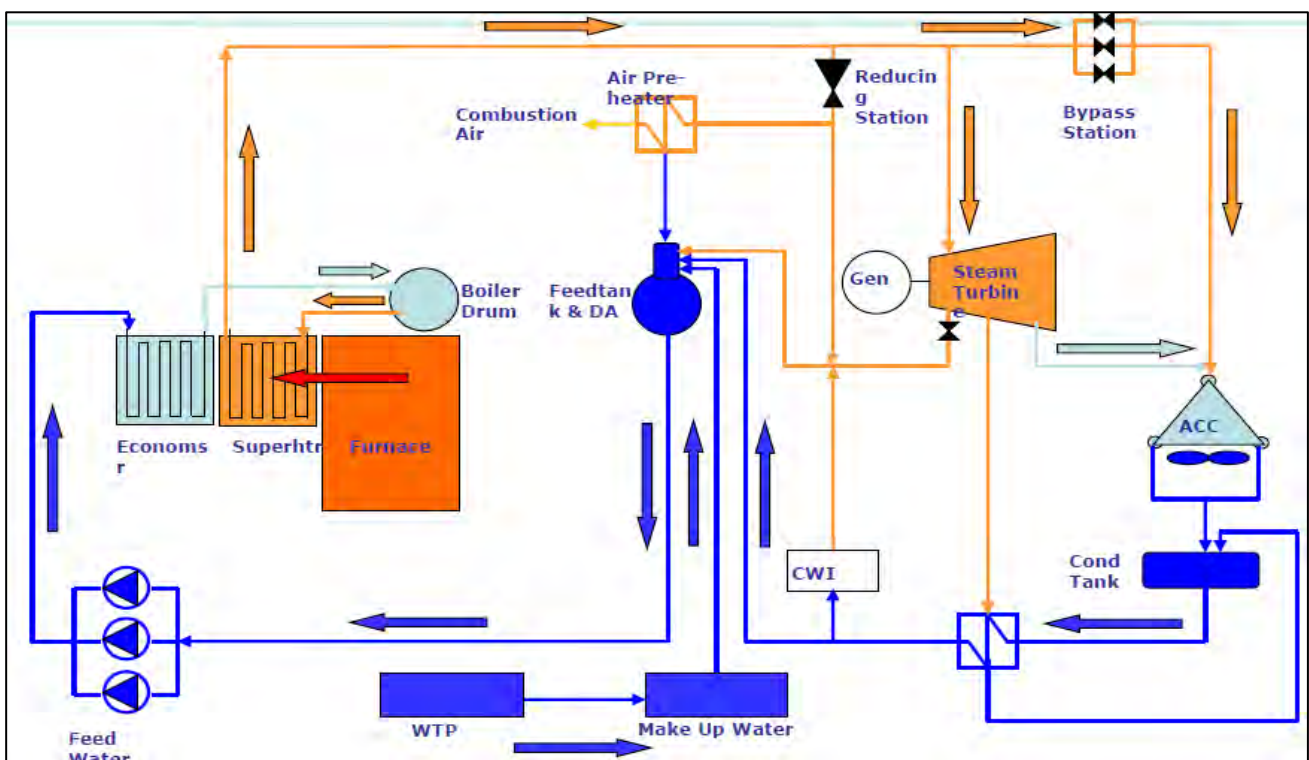
Source: Pennon Group presentation, 12th July 2011

Energy Production

The superheated, dry steam produced in the boiler travels to the steam turbine where its energy is used to drive the turbine, which in turn drives the generator set. The generator produces enough electricity to power the Lakeside facility and export 34MW onto the National Grid with approximately 3MW reused to power the Plant.

The exhaust steam from the turbine passes through an air-cooled condenser and the spent steam and the condensate returned to the boilers via a closed loop system and pumped back to the boiler making a closed-loop steam / water circuit. The facility has also been designed so that low pressure steam can be extracted from the turbine, allowing hot water to be produced to supply local consumers with heat via a district heating network, should this be viable in future. The plant would then operate in Combined Heat & Power mode with increased thermal efficiency.

Figure 2-2-3: Steam cycle layout for Lakeside



Source: Pennon Group presentation, 12th July 2011

Air Pollution Control

The plant is designed to meet the requirements of the Waste Incineration Directive (WID) as a minimum for emissions release.

The abatement system installed consists of flue gas recirculation (FGR) and selective non-catalytic reduction (SNCR) by injection of aqueous ammonia or dry urea. Acid flue gases will be neutralised by semi-dry scrubbing in a solution of lime and water. An activated carbon injection is installed on each stream to minimise the flue gas emissions of dioxins, mercury and other heavy metals. After flowing through the gas scrubber, the gases pass through bag filters to remove particulates (APC), including lime and activated carbon particles.

Following cleaning, the combustion gases are released to atmosphere via two separate flues within a 75 metre stack to ensure efficient plume dispersion. The plant was designed so that for 95% of expected weather

conditions there will be minimal or no visible plume. The stack also includes a third flue to discharge combustion gases from the adjacent clinical waste incinerator.

Ash Handling and Processing

Two types of solid waste are generated by the combustion process; incinerator bottom ash (IBA) from the grates and boilers and air pollution control (APC) residues in the form of fly ash, from the abatement equipment.

Combustion bottom ash is generated at approximately seven tonnes per hour for each line. Once quenched with water from the wastewater treatment plant and it is removed by conveyor to a covered storage area and transported by moving belts into dedicated bunkers. Ferrous metals are removed from the bottom ash by overhead electromagnets and then recycled. The bottom ash is removed from site and processed into an approved aggregate material for road building and construction.

Ash from the particulate filtration system is generated at approximately 0.9 tonnes per hour as APC residues and stored on site in sealed silos prior to removal in purpose built sealed tankers classified as hazardous waste to a permitted treatment facility where it is treated, neutralised and then placed in an appropriately permitted landfill.

Plant Performance

MSW Processed

The feedstock to the plant consists of municipal solid waste and non-hazardous commercial and industrial solid waste and residues from materials recovery, exhibiting the same characteristics as MSW. Processing capacity is approximately 410,000 tonnes per annum. The plant was designed with the capability for burning materials with an average Net Calorific Value (NCV) between 7.5 MJ/kg and 12.5 MJ/kg. The average NCV at design stage was expected to be approximately 9.2 MJ/kg.

Power and Heat Generation

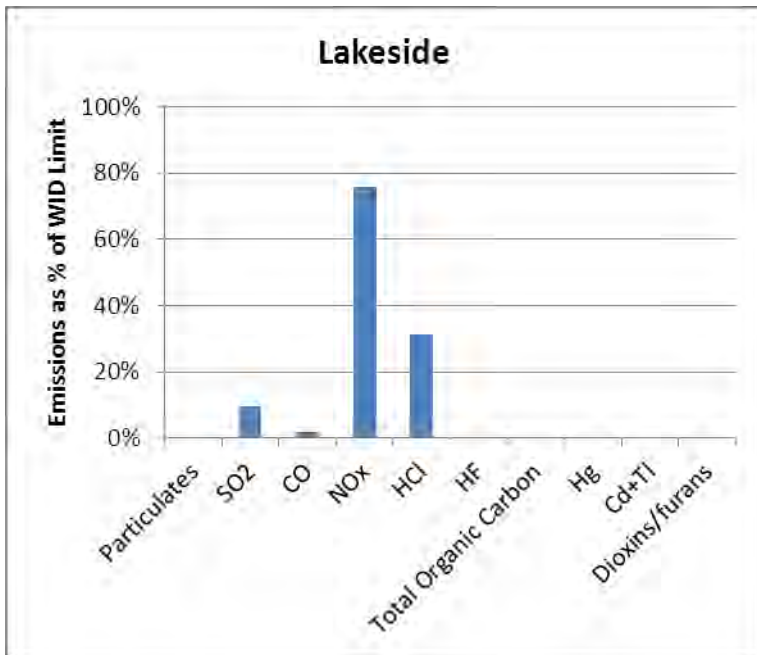
The facility generates 37MW gross of electricity providing 250,000 MWh annually the vast majority (92%) of which is exported to the National Grid, enough to meet the domestic needs of approximately 50,000 homes. Lakeside also has the potential to supply surplus heat to local infrastructure, giving it the potential to operate as a Combined Heat and Power (CHP) plant in future.

Environmental Performance

Emissions to Air

The new plant has been designed to meet the requirements of the European Waste Incineration Directive for dioxins, heavy metals, acid gases, nitrogen oxides and particulates. The following table summarises air emissions from the plant.

Figure 2-2-4: Emissions data for the Lakeside WtE plant



Source: WSP analysis of data from 1st to 25th November 2012

The data for HF, TOC, Hg, Cd+Tl, dioxins/furans is missing. Only data for the current month is available. The particulate reading of zero appears spurious but valid according to operator report.

Online continuous monitoring is carried out for particulates and Volatile Organic Carbons, Carbon Monoxide, Sulphur Dioxide, Oxides of Nitrogen, Hydrogen Chloride and Ammonia. The full suite of dioxins was tested quarterly in the first year of operation and on a six monthly basis since.

The emissions are monitored in real time using state of the art independently calibrated measuring instrumentation to ensure compliance with permitted emissions limits.

Up to date emissions data is available from <http://www.lakesideWtE.co.uk/enviromental/emissions.html>

To maintain the integrity of gaseous emissions, the plant will cease to operate if:

- Emission limit values are exceeded for a period of more than 4 hours
- Continuous monitoring equipment is out of service for more than 4 hours
- Cumulative duration of abnormal operation exceeds 60 hours in either of the above cases, calculated over one calendar year.
- Total particulates shall not exceed 150 mg/Nm³
 - Total particulates half hourly limit 30 mg/Nm³ or 10 mg/Nm³ daily average

The Environment Agency has 24 hour - 365 days per year access to emission monitoring data.

Emissions to Water

The plant has been designed so that all process water and water from maintenance activities is collected in a water re-use tank and re-used as "grey" water for non-critical purposes. The only routine discharge to foul sewer is effluent from the offices.

Emissions to Land

The solid residues of the thermal waste treatment process consist of approximately 20,000 tonnes per annum of ferrous scrap, which is sent for recycling at an approved metal recycling facility.

100,000 tonnes per annum of bottom ash are processed into an approved aggregate material for road building and construction.

The APC residues are classified as hazardous waste and are taken to a permitted treatment facility where it is treated, neutralised and then placed in an appropriately permitted landfill. The landfill regulatory controls applied in the UK are designed to prevent pollution of the environment due to leaching of polluting substances from waste such as APC residues.

Footprint and Visual Impact

At the prestigious Letsrecycle¹⁶ Awards for Excellence in Recycling and Waste Management ceremony on 20th October 2010, the Lakeside Energy from Waste (WtE) plant and education centre scooped the award for 'Innovation in design of a waste management facility'. The Lakeside WtE facility and education centre at Colnbrook, near Heathrow airport, was recognised for its forward-thinking design elements and positive impact on the local landscape.

Royal Haskoning were also awarded for the high standard of design achieved at the 2009 Structural Steelwork Design Awards for its role in the lakeside Energy from waste (WtE) plant in Berkshire. An important date in the engineering and contracting calendar, these annual awards, recognise and reward the talent of individuals and companies working with steel, to meet a wide range of industrial, commercial and transportation construction requirements.

¹⁶ Letsrecycle is a UK Journal for the waste management industry

Figure 2-2-5: View of the Lakeside waste to energy facility



Source: Pennon presentation

Figure 2-2-6: The Education Centre on the lake adjacent to the facility



Source: Pennon presentation

The circular education centre is based on concrete piles built into the corner of an adjacent lake. The Lakeside Education Centre was designed to educate and inform local communities in all aspect of recycling and waste management. It was constructed in parallel with the Energy from Waste facility and enjoys panoramic views over the surrounding lake. Activities supported by Lakeside include an educational programme managed by qualified educationalists working with local schools to deliver recycling and waste management learning opportunities linked directly to the National Curriculum.

Operability, Reliability and Availability

The Lakeside EfW facility is a state-of-the-art facility that experienced technical issues when first commissioned and was handed over to the owner in January 2010. The plant has operated commercially for almost two years with no further technical challenges reaching the ears of the media or industry experts. The plant is guaranteed to achieve an annual operation of 8,000 hours (91%) and although WSP cannot corroborate this figure we have no reason to expect that the guarantee figure was not met. The plant is a Merchant facility and operational data is considered commercially confidential. WSP did ask Grundon to provide operational hours for the past twelve months of operation but they declined.

Economics

The estimated capital cost for building the plant was £160M.

No operating cost data has been made available because as the plant is a Merchant facility such data is considered commercially sensitive by the owners.

The Lakeside plant was developed by Grundon as a merchant facility and processes both residual MSW supplied by local Councils and C&I waste obtained from the market by Grundon's waste management operations. The plant did experience some technical issues during commissioning, which has been well reported. We understand from the operators that the plant is now performing well and meeting its regulatory requirements with respect to environmental impact.

Case Study 3 – Spittelau, Vienna, Austria

Overview

In 1969, the newly founded Fernwärme Wien GmbH (formerly Heizbetriebe Wien) was commissioned by the City of Vienna to supply the city with district heating and to assume responsibility for collecting and disposing of communal waste with the thermal waste treatment plant at Spittelau, under construction at that time.

The Spittelau plant was erected at its current location in order to provide heating to the new Vienna General Hospital (AKH) situated around 2 km away. With a total installed output of 480 megawatt hours, the plant is the second largest producer of district heating connected to the Viennese network. The thermal waste treatment unit incorporated into the plant is integrated into the power grid, with a throughput of 250,000 tonnes per year of a combination of municipal and non-hazardous commercial wastes and feeding an average of 60 megawatts into the grid (base load coverage). In addition to this, 400 MW of thermal heating output can be produced in a further five gas/gas and oil-fired hot water boilers to cover peak demand.

Firstly the delivered waste arrives at the waste bunker where two bridge cranes feed the feeding hoppers (filling shafts) of the plant; a dispatcher pushes the waste onto the grate of the combustion chamber. From the overhead stream boiler the flue gases flow through an electrostatic precipitator and a three-stage flue gas scrubber into the catalytic deNO_x and dioxin destruction system before discharge via the stack. The in-house waste water treatment plant cleanses the waste water resulting from the flue gas cleaning process. The remaining solid residues are disposed of in compliance with waste regulations.

The key outputs are as follows:

- 40,000 MWh of electricity
- 480,000 MWh of district heating
- 6,000 tonnes of scrap iron, and
- 60,000 tonnes of clinker, ash and filter cake.

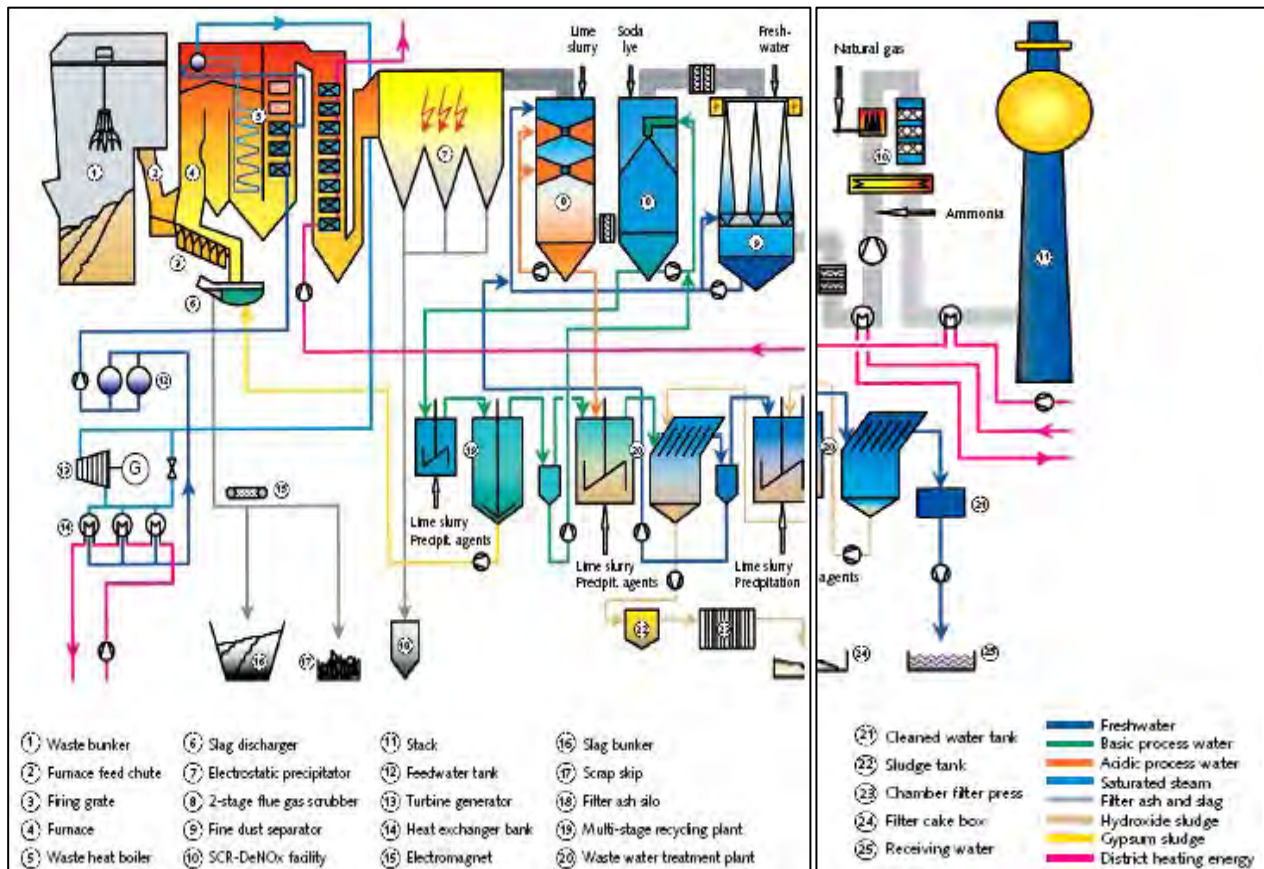
In 1987, a large section of the Spittelau plant was destroyed by fire i.e. the flue gas cleanup system, two hot water boilers and a large part of the building itself. On reconstruction the plant was fitted with a flue gas scrubbing system, as well as a state-of-the-art denitrification and dioxin destruction plant. At the same time, the external façade of the entire district heating plant was redesigned by the famous painter and architect Friedensreich Hundertwasser. The previously mundane structure was transformed into an impressive work of art, highlighting how a harmonious balance could be struck between technology, ecology and art. Spittelau has since become an integral part of the city's landscape, attracting an increasing number of tourists.

In 2001, a partnership was established between the waste incineration plant at Spittelau and Maishima Osaka Plant (MOP) resulting in the latter also being "beautified" by Friedensreich Hundertwasser. The partnership between the two incineration plants at Spittelau and Maishima Osaka Plant (MOP) was established primarily for the purpose of exchange of information on the following:

- Operational management (energy reuse, waste management etc.)
- Operational experience with various technologies
- Dealing with the public, and
- Passing on Hundertwasser's ideas and visions to posterity.

The Process

Figure 2-3-1: Schematic process flow diagram for the Spittelau facility



Source: http://www.wienenergie.at/media/files/2008/technik-bro-spittelau%20-%20englisch_9396.pdf

Figure 2-3-2: Spittelau waste to energy plant technical data

| | | |
|-------------------------|--|---------------------|
| Weighing device | Weighbridge, number: | 2 |
| Waste bunker: | Capacity: | 7,000m ³ |
| | Tipping points: | 8 |
| Combustion chamber feed | Bridge crane with hydraulic polyp grabs, number: | 2 |
| | Capacity per grab: | 4 m ³ |
| Firing | Number of combustion lines: | 2 |
| | Maximum throughput capacity per line: | 18t/h |
| Grate | Air cooled twin-track reciprocating grate: | |
| | Grate length: | 7.5m |
| | Grate width: | 4.6m |
| | Inclination: | 26° |

| | | |
|-----------------------------------|---|--|
| Combustion chamber | Fuel thermal output per line: Waste thermal value: Primary air heating: | 41.1MW 8,200 – 9,600 kJ/kg 180°C |
| Slag removal | Ram-wet slag remover Slag remover volume: | 5m ³ |
| Waste heat boiler | Natural circulation radiation boiler Maximum steam output per line: Maximum operating pressure: Maximum operation temperature: Heating surface: | 44t/h (saturated steam) 34 bar 245°C 2,420m ² |
| Turbine and generator | Saturated steam back-pressure turbine Maximum electrical output: Back pressure: | 6.4MW 4.5 bar |
| Flue gas cleaning | Number of lines: Flue gas volume per line: | 2 (deNOx plant: 1) 85,000 sm ³ /hr (wet) |
| Electro-static precipitator | Operating voltage: Dust separation efficiency: | 60kV >99.5% |
| Flue gas wet scrubber | 1st stage: | Quencher/separation of hydrogen chloride (HCl), hydrogen fluoride (HF), dust, heavy metals |
| | Design: Absorption agents: HCl separation rate: | Cross-flow scrubber Water/lime slurry >98% |
| | 2nd stage: | Separation of sulphur dioxide (SO ₂) |
| | Design: Absorption agents: SO ₂ separation rate: | Counter-current NaOH solution >98% |
| DeNOx & dioxin destruction system | SCR catalytic converter, number of catalytic converter systems: Operational temperature: NOx destruction rate: Dioxin destruction rate: | 3 280°C >95% >95% |
| Chimney | Design: Height: Diameter: | Steel/brick 126m 2.5m |

Waste reception, storage and feeding

The storage area of the plant receives municipal solid waste, light commercial waste and bulky waste from 250 waste vehicles Monday to Friday 7am to 3pm. Delivery vehicles pass over one of two weighbridges before discharging into the 7,000 m³ waste bunker from one of a total of eight tipping points. It has bunker capacity large enough for three delivery-free days. Following thorough mixing in the bunker (in order to homogenise the wastes and provide a more stable calorific value within the feedstock) the waste is transferred to the two incineration lines by one of the two bridge cranes each with a grab capacity of 4 m³.

The exhausting of the fresh air required for the incineration process from the waste bunker maintains the latter in a constant state of partial vacuum, thus minimising odour and dust emissions from the tipping points into the ambient air.

Combustion

The facility consists of two incineration lines, each with a flue gas treatment plant and a SCR-DeNO_x system including a dioxin destruction facility serving both lines. This is connected to the treatment plant for the waste water from the flue gas wet scrubber. The waste moves from the bunker to the firing grate via the furnace feed chute and hydraulic ram feeder. Up to 17 tonnes of waste per hour can be thermally treated on the inclined, 35 m² Martin two-track reverse-acting grate. The pre-heated (180°C) combustion air is injected from beneath the grate; the secondary combustion air is injected over the combustion bed from the side to guarantee good burnout of the organic in the flue gas.

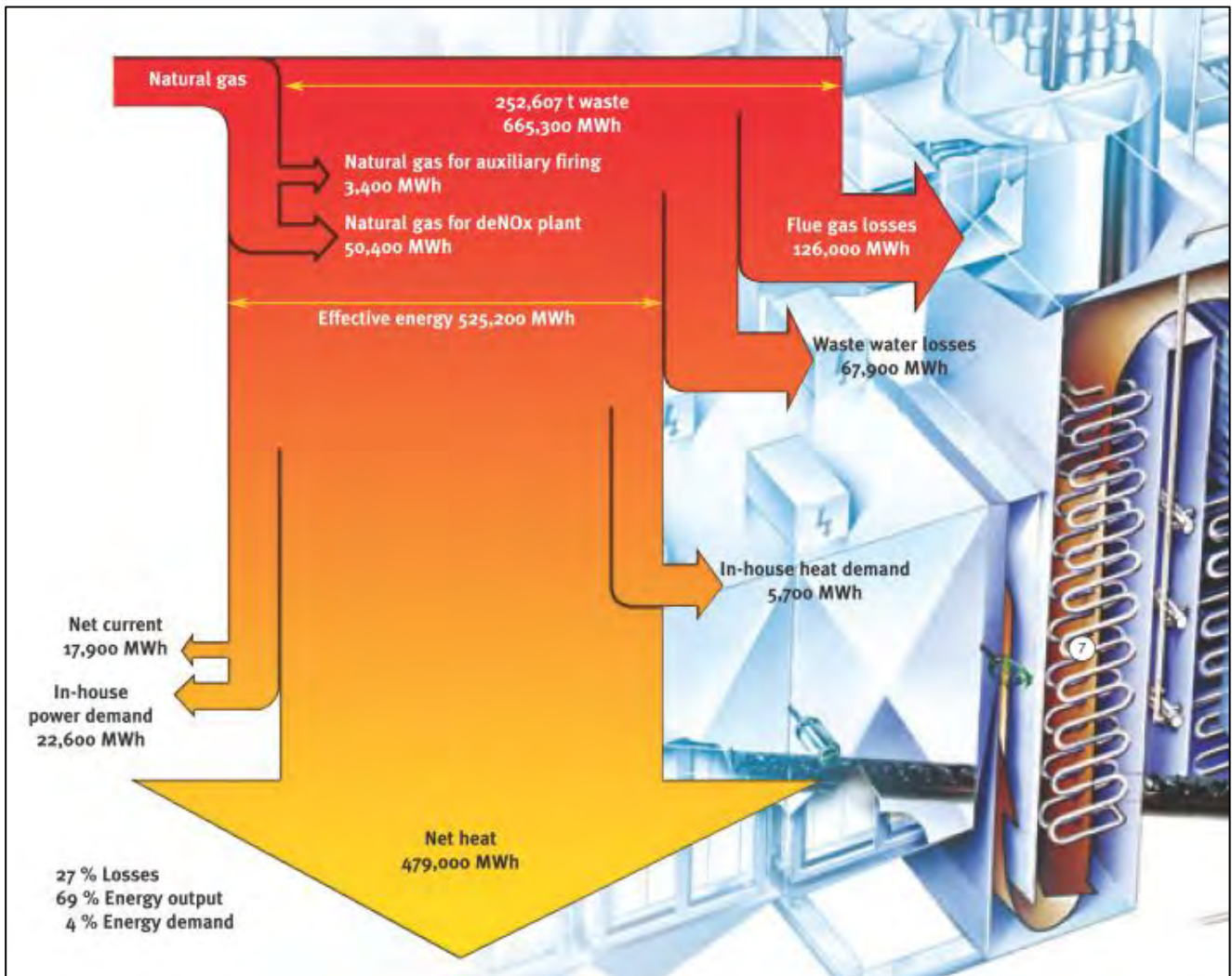
During the start-up and shut-down phase two 9 MW gas burners ensure the necessary combustion chamber temperature and thus the burn-off of the flue gases required by law. In normal operation the use of the gas burners is not necessary: the average waste heating value (CV) of 9,500 kJ/kg is more than sufficient to ensure self-combustion of the waste.

The 850°C flue gas transfers its heat to the boiler. Both lines generate a total of 90 tonnes per hour of saturated steam at 34 bar. During power generation, this steam is reduced to 4.5 bar in a back pressure turbine; then the heat in the low pressure steam is transferred to the returning water of the district heating network by means of condensation in the heat exchanger bank.

Energy Production

Averaged over the year, approximately 6 MW of power is required to meet the parasitic load of the plant and feeding into the public grid as well as 60 MW of heat for district heating. This amount of energy is equivalent to a space heating equivalent of some 60,000 dwellings with 80 m² floor area.

Figure 2-3-3: The Annual Energy Balance for 2006



Source: http://www.wienenergie.at/media/files/2008/technik-bro-spittelau%20-%20englisch_9396.pdf

Air Pollution Control

When commissioned in 1971, the thermal waste treatment plant already had a highly effective electrostatic precipitator but in 1986 this was augmented by a 2-stage flue gas scrubber with a downstream fine dust separator (Electrodynamic Venturi). By retrofitting these 3 treatment stages and installing Europe's first SCR-DeNOx facility in 1989, the Spittelau plant became an international leader in flue gas cleaning and emission reduction for thermal waste treatment plants. From the outset, emissions from the existing process were significantly lower than the emission limit values for domestic waste-fired steam boiler plants imposed by the Austrian Clean Air Act a year earlier.

The flue gas leaves the first heat exchanger downstream from the waste heat boiler at a temperature of 180°C, and is initially cleaned by the 3-stage electrostatic precipitator to a dust content of < 5 mg/Nm³. The filter ash is then transferred to a 125 m³ silo via a mechanical-pneumatic conveyor system.

The flue gas then enters the quencher of the first scrubber, cooling it to saturation temperature (60 - 65°C) by open-circuit water injection. The first scrubber, operated at a pH value of one, removes hydrogen chloride (HCl), hydrogen fluoride (HF) and dust, as well as particle-bound and gaseous heavy metals, through intensive cross-flow gas/liquid contact.

The second wet scrubber is designed as a counter-current scrubber and is operated with a pH value of seven. This results in the efficient absorption of sulphur dioxide (SO₂) from the flue gas. In the next cleaning stage (the Electrodynamic Venturi) adiabatic expansion of the flue gas takes place and then the fine dust particles, which have been moistened and charged by a central electrode, are removed to reduce the residual dust content to values < 1 mg/Nm³ (dry). The second heat exchanger reheats the flue gas to 105°C and passes it via the induced draft fan to the deNOx and dioxin destruction system.

The DeNOx facility is the final stage of the flue gas treatment process and utilises selective catalytic reduction (SCR). The flue gas streams from both treatment lines are combined, mixed with vaporised aqueous ammonia (NH₃) and heated to a reaction temperature of 280°C by a heating tube and gas duct burners.

Passing through the three catalytic converter stages causes the nitrogen oxides (NOx) to react with the added ammonia and the oxygen in the flue gas to form nitrogen and steam. This also results in dioxin/furan destruction. The resultant exhaust gas is then cooled to 130°C in the third heat exchanger and finally released into the atmosphere through a 126 m high stack.

Ash Handling and Processing

The incombustible components (about 60,000 tonnes per annum of bottom ash/slag) discharged from the end of the combustion grate are quenched in the water-filled slag discharger. From there, the cooled bottom ash is transported to a bunker by a conveyor belt, after removal of the ferrous scrap by overhead electromagnets. About 6,000 tonnes per annum of ferrous scrap are recovered every year.

Plant Performance

MSW Processed

The plant receives and processes in excess of 250,000 tonnes per annum of predominantly MSW.

Table 2-3-1: The mass and energy balance per tonne of MSW (2006)

| Input Flow Relating to 1 Tonne of Waste | |
|--|-------------------|
| Heat requirement (covered by in plant generation) | 25 kWh |
| Power requirement (covered by in-plant generation) | 90 kWh |
| Natural gas requirement | 20 m ³ |
| Freshwater requirement | 746 litres |
| Lime consumption | 2.6 kg |
| Consumption of sodium hydroxide solution, 30% | 2.4 kg |
| Consumption of ammonia, 25% | 3.0 kg |
| Consumption of precipitation agents | 0.2 kg |
| Output flow (relating to 1 Tonne of waste) | |
| Heat output | 1,896 kWh |
| Power output | 34 kWh |
| Slag and Gypsum | 205 kg |
| Ferrous Scrap | 22 kg |

| | |
|---------------------|------------|
| Filter Ash | 17 kg |
| Filter Cake | 1 kg |
| Cleaned Waste Water | 357 litres |

Source: http://www.wienenergie.at/media/files/2008/technik-bro-spittelau%20-%20englisch_9396.pdf

Power and Heat Generation

Around 40,000 MWh of electricity and 470,000 MWh of district heating are produced each year. The quantity of heat is enough to provide heating for over 60,000 households in Vienna each year.

Environmental Performance

Emissions to Air

Continuous monitoring is undertaken for emission values of carbon monoxide, sulphur dioxide, nitrous oxides, hydrogen chloride, dust and hydrocarbon in the purified flue gas. These are transmitted online to the City of Vienna environmental agency, thus enabling on-going monitoring of the maintenance of limit values. The emission values for these key parameters are also displayed on a large screen adjacent to the facility to enable the public to see current levels at any time.

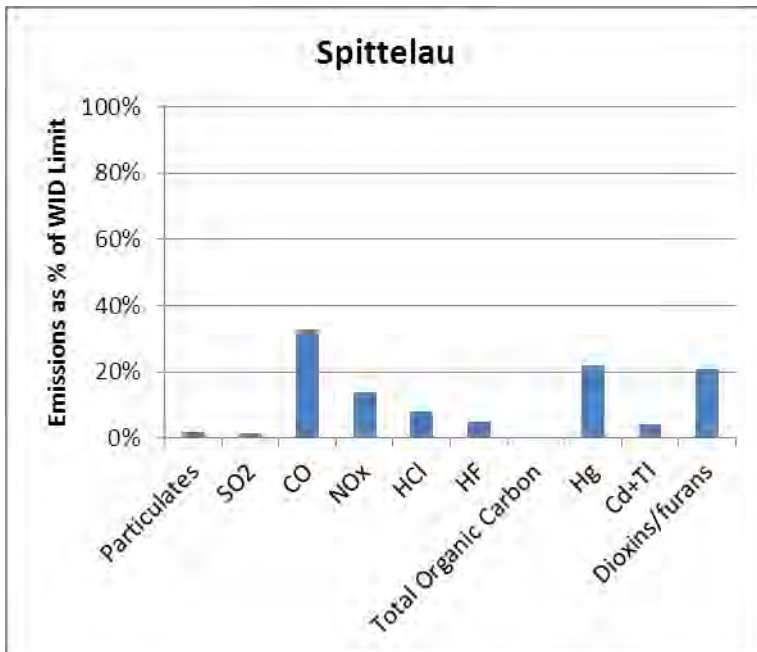
Figure 2-3-4: The real time emission levels display outside of the main gate of the facility



In normal operations emissions from the plant are significantly below those limit values stipulated by law relating to air pollution control are significantly undershot (and are compliant with the Austrian Clean Air Act 1988, the first worldwide and widely discussed emission limit values for dioxins and furans).

With its high flue gas cleaning standard and substitution of primary energy sources such as gas or oil with waste as a fuel, the incorporation of the Spittelau plant into the City of Vienna's district heating network has resulted in an improvement in the municipal emission and emission balance sheet.

Figure 2-3-5: Emission values in the stack gas (2006) at Spittelau



Source: WSP analysis of data from http://www.wienenergie.at/media/files/2008/technik-bro-spittelau%20-%20englisch_9396.pdf

The following link provides current emission values updated every half an hour:

<http://www.wienenergie.at/fwapp/emissionen/spittelau.htm>

Emissions to Water

A multi-stage treatment plant processes all the waste water arising in the flue gas wet scrubbing system. This is then passed into the receiving water course (Danube Canal). With the addition of lime slurry, special precipitation and flocculation chemicals, a precipitation reactor first converts the dissolved heavy metal compounds present in the waste water into an insoluble form. In the downstream lamella clarifier the suspension formed is separated into overflow water and heavy metal hydroxide sludge. After repeatedly passing through precipitation and separation stages, the hydroxide sludge dewatered in a chamber filter press to residual moisture of approx. 30 % and removed as filter cake. Following final control of the volume, temperature, pH and conductivity the purified waste water is passed into the receiving water course.

The multi-recycling plant processes the sodium sulphate discharge water of the second wet scrubber stage. The dissolved sodium sulphate is precipitated by the addition of lime slurry, sedimented in the settling tank and pumped into the wet slag remover as gypsum sludge. The sodium hydroxide solution reclaimed during the course of the sedimentation process is fed back into water cycle of the second wet scrubber.

Emissions to Land

The solid residues of the thermal waste treatment are slag, ferrous scrap, fly ash and filter cakes with a total mass of some 250 kg per tonne of waste utilised. After the slag has been removed to a special treatment plant (in covered dumper trucks), this residue is sifted, freed of any remaining ferrous scrap, mixed with cement and water and used as slag concrete, with an eluate quality approaching that of drinking water, in landfill site preparation (perimeter wall formation).

The ferrous scrap previously separated from the raw slag in the Spittelau plant is returned to the material cycle (steel production). The residues from the waste water treatment plant, the filter cakes and the fly ash are transported abroad by train in covered skips or silo transporters and deposited in a decommissioned salt mine.

Footprint and Visual Impact

Following the 1987 fire at the plant, the outer façade was re-designed by the painter and architect Friedensreich Hundertwasser (see Figure 2-3-6). The previously functional structure was transformed into a unique work of art which is an example of a fusion of technology, ecology and art, and makes a major contribution to the reduction of 'visual pollution' of the urban environment.

Figure 2-3-6: Photographs of the Spittelau waste to energy plant



Source: Martin GmbH

The Spittelau plant has also acted as the inspiration for a facility in Osaka in Japan where Hundertwasser again provided the architectural treatment.

Figure 2-3-7: The Maishima Incineration Plant in Osaka



Source: Martin GmbH

Operability, Reliability and Availability

Very little operational data is available. The availability data presented in Table 2-3-2 has been found on the internet. WSP would prefer to present real actual operating data and we have tried to contact the plant by telephone on several occasions but without success.

Table 2-3-2: Availability data for 2006

| | |
|---------------------------------------|---------|
| Waste throughput rate (tonnes) | 252,607 |
| Operational hours incineration line 1 | 7859 |
| Operational hours incineration line 2 | 7784 |

Source: http://www.wienenergie.at/media/files/2008/technik-bro-spittelau%20-%20englisch_9396.pdf

Economics

No economic data is available for the Spittelau facility.

The main reason for including the Spittelau plant as a Case Study was because of the architectural treatment of the plant to gain public acceptance. The age of the plant would exclude it from inclusion based on performance.

However, public perception and acceptance of WtE plants is very important so we have included photographs (in the table below) of other facilities that incorporated innovative architecture to gain public acceptance. There are other plants included as Case Studies that also employ innovative architecture:

- *Lakeside, UK*
- *ISSEANE, France*
- *Allington, UK*

Further examples are provided on the following page.

Figure 2-3-8: WtE plants with innovative architectural treatment



Cleveland, Teeside, UK



Marchwood, Hampshire, UK



Shenzhen, China



Boblingen, Germany



Esbjerg, Denmark



Hengelo, The Netherlands



Pali, Taipei, Taiwan



Rotterdam, The Netherlands



St Ouen, Paris, France



Hirano, Osaka, Japan



Isle of Man, UK



Tokyo, Japan

Source: Various

Case Study 4 – Allington, Kent, UK

Overview

The Energy from Waste facility at Allington Kent is operated by Kent Enviropower Limited (a part of FCC Environment) and is built in a former quarry, the site includes one 80 metres high chimney, and covers an area of 34 hectares, of which 27 hectares will eventually become parkland, and permanently employs around 100 people.

The facility can take up to 500,000 tonnes a year of non-hazardous waste from households and businesses in and around Kent for energy recovery, and up to 65,000 tonnes per year of source separated recyclables (paper, card, metals and plastics).

The majority of the waste treated (over 325,000 tonnes per year) is household waste managed by Kent County Council from the Council areas of Maidstone, Sevenoaks, Tunbridge Wells, Tonbridge and Malling, Dartford, Gravesham and Swale.

In 2000, Kent County Council granted planning permission for the project and the Integrated Pollution Prevention and Control permit from the Environment Agency was granted in 2002.

Testing and commissioning of the facility was completed in late December 2008 and the facility is now operational.

The key outputs are as follows:

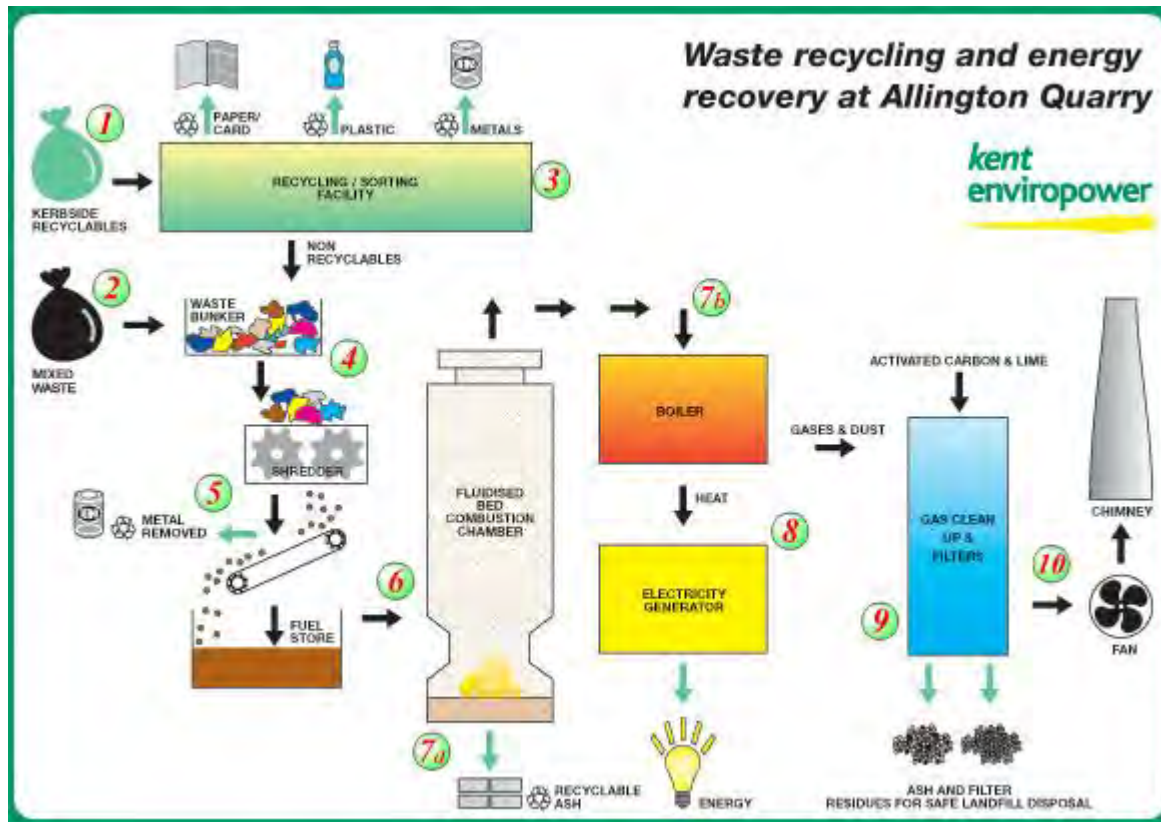
- 43MW of power, 34 MW of which will go into the local electricity supply network;
- Chimney emissions - meet or are better than existing EU standards;
- Types of ash generated - Bottom ash, and flue gas treatment residues;
- Amount of ash generated - Up to 25% of waste by weight, and;
- 60,000 tonnes per annum of bottom ash will be recycled.

Suppliers and EPC contractors involved with the project:

- Boiler/incinerator system supplier: Lurgi (licensee of Ebara, Japan);
- Turbine/Generator supplier: Siemens;
- EPC: Lurgi, Hochtief.

The Process

Figure 2-4-1: Process schematic of the Allington WtE Facility



Source: www.kentenviropower.co.uk

Waste reception, storage and feeding

The storage area of the plant receives non-hazardous waste from municipal and commercial and industrial sources via a maximum number of permitted vehicle movements of 582 per day (291 movements in and out of the plant).

All unsorted waste is processed as follows:

- all waste is processed through one or three waste pre-treatment lines with shredders and metal separation;
- separated recyclable materials are transferred to the on-site MRF;
- pre-treated waste is placed in a waste storage bunker, and;
- pre-treated waste is placed into one of the three fluidised bed combustion chambers using cranes to load the feed hoppers.

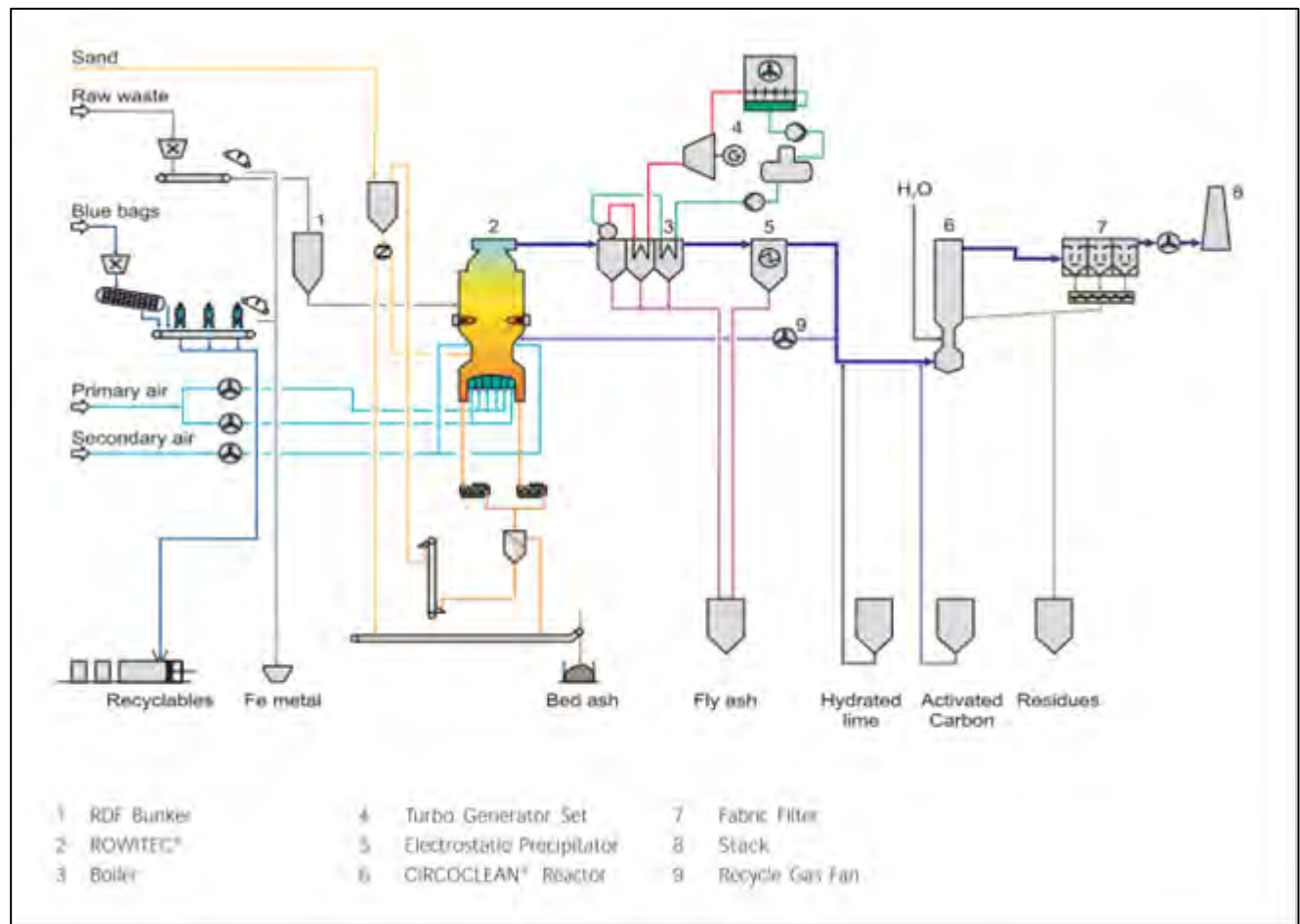
Combustion

The facility consists of three combustion lines, with a flue gas cleaning plant employing the CIRCOCLEAN technology which ensures the achievement of the emissions limits set out in the permit.

The combustion process is based on rotating fluidised bed technology (ROWITEC) licensed from Ebara by Lurgi Lentjes with the possible injection of urea for NO_x reduction into the freeboard.

The process description provided by Lurgi Lentjes is shown below:

Figure 2-4-2: Process schematic of the Allington waste to energy plant



Source: Lurgi Lentjes

The technology employed at Allington is the TIF¹⁷ fluidised bed technology. Ebara has built almost 100 TIF plants in Japan and there are several examples of the technology in Europe demonstrating that the technology is fully proven. There is a similar three line plant in Madrid which has been operating for many years.

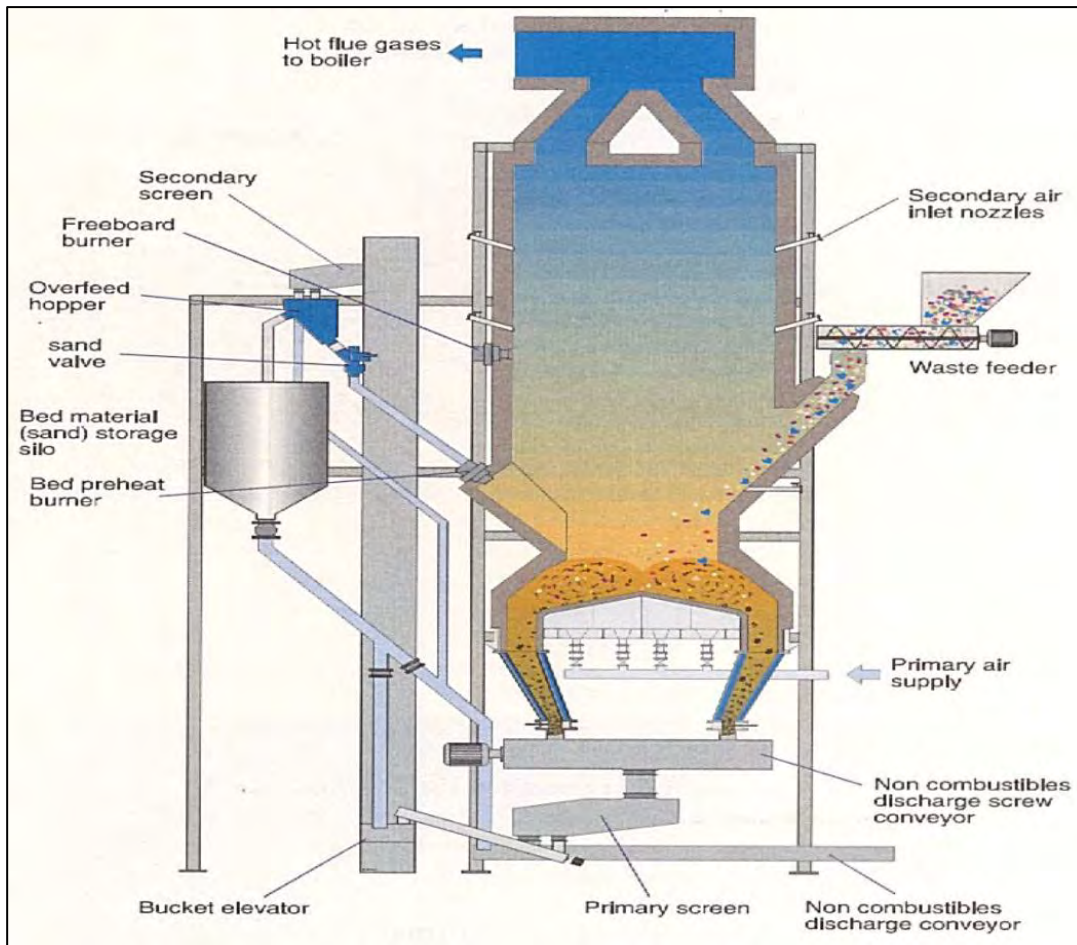
The internal geometry at the air distribution part of the fluidised bed produces a highly turbulent toroidal mixing regime, which according to Ebara employs the advantages of the BFB¹⁸ and CFB¹⁹ designs to produce an optimised design of fluidised bed.

¹⁷ Twin Interchanging Fluid

¹⁸ Bubbling Fluidised Bed

¹⁹ Circulating Fluidised Bed

Figure 2-4-3: Schematic of the TIF fluidised bed



Source: Ebara

Table 2-4-1: The original design parameters for the Allington plant

| Emissions (daily and sampling period average respectively): | | | Technical Data: | | |
|---|---------|-------------------------|-----------------------------|------------|----------|
| SO ₂ | 50 | mg/m ³ (STP) | Total plant capacity | 530,000 | Mg/a |
| NO _x (without/with SNCR) | 200/150 | mg/m ³ (STP) | Capacity sorting plant | 30,000 | Mg/a |
| CO | 50 | mg/m ³ (STP) | Capacity incineration plant | 500,000 | Mg/a |
| Dust | 10 | mg/m ³ (STP) | No. of lines | 3 | |
| HCl | 10 | mg/m ³ (STP) | Thermal capacity per line | 53.8 | MW |
| HF | 2 | mg/m ³ (STP) | Calorific value range | 6.5 - 12.5 | MJ/kg |
| TOC | 10 | mg/m ³ (STP) | normal | 9.07 | MJ/kg |
| NH ₃ | 10 | mg/m ³ (STP) | Live steam parameter | 420 / 65 | °C / bar |
| Hg | 0.05 | mg/m ³ (STP) | Power export | approx. 34 | MW |
| Cd, Ti | 0.05 | mg/m ³ (STP) | | | |
| Other heavy metals: | 0.5 | mg/m ³ (STP) | | | |
| Dioxins/Furanes: (TEQ) | 0.1 | ng/m ³ (STP) | | | |

Source: Lurgi Lentjes

Energy Production

The plant produces 43MW of power and making allowances for parasitic load, 34MW will be exported to the local electricity supply network. The exported electricity will be sufficient to power the town of Maidstone with some 30% left over.

Currently the potential thermal energy output of 53.8MW per line is not utilised.

Air Pollution Control

The three TIF incineration lines have the facility to inject urea into the afterburner chamber to reduce NO_x emissions. Electrostatic precipitators are used for pre-separation of fly ash downstream of the horizontal three-pass boiler. The flue gas cleaning plant with CIRCOCLEAN technology ensures the achievement of the emissions limits set in the permit.

The plant is fully compliant with WID. The plant operator publishes the Continuous Emissions Monitors reports on a monthly basis on their website: <http://www.kentenviropower.co.uk/enviropower.asp?ID=59>)

Ash Handling and Processing

As a result of the incineration process up to 25% by weight of the input materials will become ash which will require further treatment. Approximately 60,000 tonnes per annum of bottom ash will be generated annually which will be recycled by a specialist contractor.

Air pollution control residues and filters will be treated and disposed of in suitably licensed landfill sites.

Plant Performance

MSW Processed

The plant is designed to treat up to 500,000 tonnes per annum of residual MSW and similar commercial and industrial waste with a calorific value range of 6.5 – 12.5 MJ/kg. The MSW treated at the facility has been collected from households and premises where recyclable materials have already been segregated and additional segregation of ferrous metals occur at the site following shredding prior the waste being introduced into the combustion chamber.

Power and Heat Generation

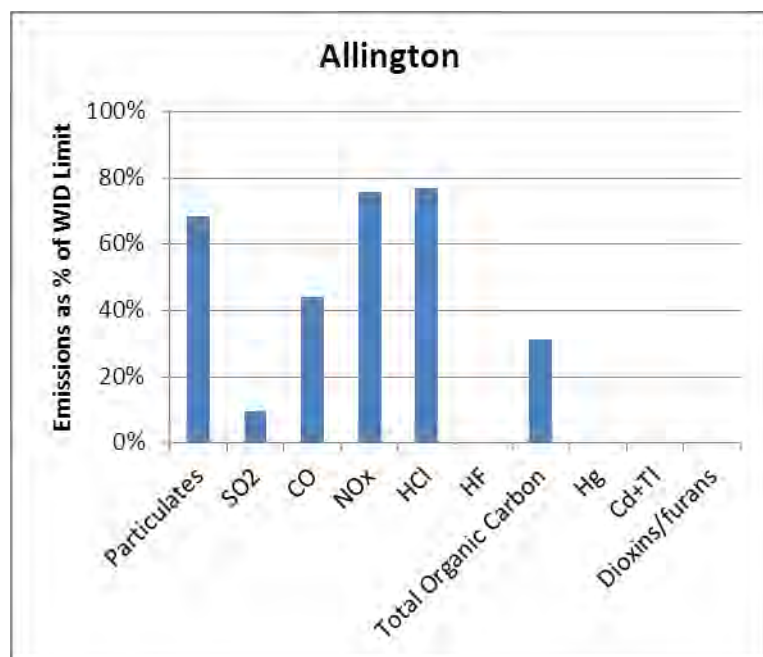
The plant will generate approximately 43MW of electricity of which 34MW will be exported to the local supply network. The plant also has the capacity to generate a thermal capacity per line of 53.8MW. This is currently not utilised.

Environmental Performance

Emissions to Air

The following data is based on the Monthly Maximum emissions published by Kent Enviropower on their website (<http://www.kentenviropower.co.uk/enviropower.asp?ID=59>).

Figure 2-4-4: Emissions to air



Source: WSP analysis of Allington data

The reporting period was from April 2011-March 2012. Data for HF, Hg, Cd+Tl, dioxins/furans were missing. The plant meets the WID limits but emissions of particulates, CO and TOC are relatively high.

Emissions to Water

No data available but the plant uses a dry scrubbing system for flue gas cleaning and therefore the only liquid effluent produced will be blowdown from the boiler.

Emissions to Land

The solid residues of the thermal treatment process consist of 60,000 tonnes per annum of bottom ash and air pollution control residues (including filters).

The bottom ash is reprocessed and is recycled in the construction aggregates and similar and the APC residues are treated and disposed on to a licensed landfill site.

Both the bottom ash and APC residues are transported as required by the plants permit and appropriate transportation regulations.

The table below summarises the waste disposal and recovery data for 2008.

Table 2-4-2: Waste disposal and recovery at Allington

| Reporting of Waste Disposal and Recovery for the year 2008 | | | |
|--|----------------|---|-----------------|
| Permit Reference Number : BR4551 | | Operator : Kent Enviropower Ltd | |
| Installation : Allington Quarry | | Form Number : Agency Form / BR4551 / R1 / Form Dated 12 January 2006. | |
| Waste Description | Disposal Route | Tonnes | Recovery Tonnes |
| 1) Hazardous Wastes | | | |
| APC residues | Landfill | 15619 | 0 |
| Other hazardous wastes | N/A | 0 | 0 |
| Total hazardous waste | | 15619 | |
| 2) Non-Hazardous Wastes | | | |
| Bottom Ash | Recycle | 13189 | 13189 |
| Dirty Ferrous | Recycle | 4812 | 4543 |
| MRF Materials | Recycle | 16126 | 12742 |
| Other non-hazardous wastes | N/A | 0 | 0 |
| Total non-hazardous waste | | 34127 | 30474 |
| TOTAL WASTE | - | 49746 | 30474 |

| Trends in Waste Disposal and Recovery | | | |
|---------------------------------------|------------------|-------------|-----------------------|
| | Named Waste | Total Waste | Waste per unit output |
| Total Haz 2006 | APC Residue | 6939 | |
| Total Haz 2007 | APC Residue | 23184 | |
| Total Haz 2008 | APC Residue | 15619 | |
| Total Non Haz 2006 | Bottom Ash & MRF | 20365 | |
| Total Non Haz 2007 | Bottom Ash & MRF | 39487 | |
| Total Non Haz 2008 | Bottom Ash & MRF | 34127 | |

| | | | |
|---|--|--|--|
| Operator's comments : | | | |
| Non haz waste – Dirty Ferrous 269 tonnes were landfilled reducing recovery to 4543 tonnes. | | | |
| MRF materials – 3384 tonnes rejected through the process reducing recovery to 12742 tonnes. | | | |

Source: Kent Enviropower Annual Report for Allington Energy from Waste Facility. 2008

Footprint and Visual Impact

The total site area is approximately 84 acres, however 67 acres is proposed to become parkland. The building appears to have a very low profile considering it houses three very tall fluidised bed combustors and has been constructed so that it is partly below natural ground level to minimise the visual impact on the surrounding area and a site has also be screened on the southern elevation with trees.

Figure 2-4-5: Photograph of the Allington site



Source: Lurgi Lentjes

Operability, Reliability and Availability

Similar to the Lakeside EfW plant described in Case Study 2, the Allington plant also experienced technical challenges, particularly relating to the refractory lining of the FB combustor and the flue gas cleaning system. The initial operation in 2009 achieved availability of only 65 – 70%²⁰.

The plants supplied by Ebara in Japan are typically designed to process the required design throughput in 300 days of operation with the remainder of the year used for shutdown and maintenance. This equates to an annual availability of 82%.

Availability data was requested from the operator but none was provided.

Economics

The project has cost more than £150 million.

No operating cost data has been made available because it is considered commercially sensitive by the operators.

The Allington plant is the largest fluidised bed combustion plant outside of Japan, which although it suffered from some initial teething problems has operated successfully for the past few years and met most of its environmental objectives. The plant has a very low building profile thanks to the fact that most of the fluidised bed combustors and boilers have been sunk 30 metres into the ground.

²⁰ Tolvik: Waste Market Watch – EfW Operational performance, 2011

Case Study 5 – Issy les Moulineaux, Paris, France

Overview

The Issy les Moulineaux Waste to Energy plant (known as ISSEANE) is located close to the bank of the River Seine, a few kilometres from the centre of Paris, France. The plant was commissioned in 2007 and processes 460,000 tonnes per year of MSW from the city making it the largest WtE plant in France. The plant is owned by Syctom Paris, a co-operative incorporating 85 communities which manages the 2.7 million tonnes of waste produced by Parisian households each year. The plant is operated by TIRU Group.

The sensitive location of the plant required careful design and unique architectural treatment for a plant of this type and size. To enable the plant to fit into the surroundings it is buried 31m underground resulting in an elevation of just 21m above ground level, roughly equivalent to the height of a 6-story building. Furthermore, the twin stacks are only a few metres above roof level and well hidden. A 'green roof' and heavy tree planting on the site and building itself further helps the plant blend in to the surroundings. Not only is the design unique for an waste to energy plant of this scale, but the location presented a major engineering challenge due to the high water table, constrained site and stringent emissions requirements which are well below WID limits.

The plant provides electricity and heat to the surrounding area, has very low emissions and high efficiency. However, the state-of-the-art features resulted in a very high capital cost relative to more conventional waste to energy plants.

Figure 2-5-1: Photographs of the ISSEANE plant



Source: Hitachi Zosen Inova

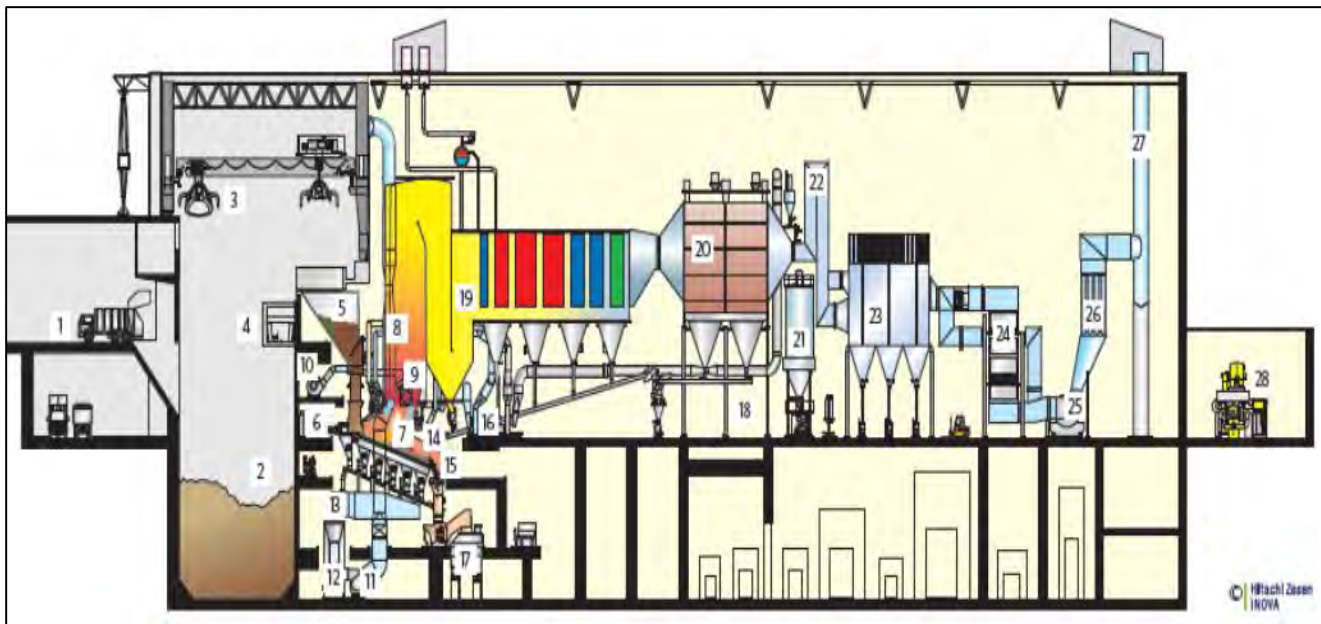
The Process

The plant is a two-line water-cooled grate incinerator, incorporating a conventional steam cycle. The two lines have a combined thermal capacity of 170MW, and steam is passed to a single 52MW controlled extraction condensing steam turbine to generate electricity as well as enabling the offtake of low pressure steam to supply 80,000 households with heat via a hot water district heating network.

Planning conditions required novel design and architecture, as well as a state-of-the-art gas cleaning system which allows for a lower stack than normal.

The diagram below shows the layout of the plant, demonstrating the relatively low profile design achieved by the use of a horizontal boiler.

Figure 2-5-2: Process schematic of the ISSEANE plant



Source: Hitachi Zosen Inova

Waste reception, storage and feeding

Residual waste is transferred by truck to a single bunker in the plant, which has a capacity of 20,000 m³. Two crane grabs sort the waste and transfer it to the feed hopper and then onto the grate.

In addition there is a sorting and recycling facility on the site which handles 50,000 tonnes of material per year.

Combustion

Waste is combusted on one of two Hitachi Zosen Inova water-cooled grates. Each grate measures 10m by 10m and has five zones, the initial three being water cooled. Hot gases then exit the furnace into a secondary combustion chamber and are transferred through a 4-pass horizontal boiler. This system has a relatively low profile which helps to minimise the building height.

The sophisticated combustion control system includes an infrared camera to monitor combustion and enable adjustments to be made to respond to varying waste feedstock and optimise burn-out.

Energy Production

The flue gases are passed through the boiler, cooling the gas from 1,100°C to around 200°C and raising steam. The two lines produce a total of 200 tonnes per hour of superheated steam at 400°C and 50 bar which is passed to a single Alstom 56MW condensing turbine. The turbine incorporates an offtake for low pressure steam, considerable quantities of which are used to generate hot water to supply 80,000 households with heating and hot water via a district heating network.

A water cooled condenser uses water from the River Seine to condense the turbine exhaust gases, which is subsequently returned to the river.

Air Pollution Control

The plant has a state-of-the-art emissions control system in order to meet the stringent emissions limits required at the plant, which are guaranteed to be 50% below future European emissions limits (hence significantly lower than WID for most pollutants).

Flue gases are first passed through an electrostatic precipitator (ESP) which removes the vast majority of particulate matter (around 99%). A dry sorption sodium bicarbonate system neutralises acid gases (in particular SO₂), and an activated carbon system further removes pollutants and dioxins in particular. A fabric filter removes particulate matter not captured by the ESP and products from the acid gas removal and activated carbon systems. Finally, a low temperature Selective Catalytic Reduction (SCR) deNO_x system removes a proportion of NO_x in the flue gases by injection of ammonia in the presence of a catalyst at around 220°C. The cleaned gas then exists via the two low profile stacks. In order to prevent a plume from forming, a reheat gas burner is included to raise the temperature of the exit cleaned flue gas (to a maximum of 290°C) to prevent the formation of water vapour at the stack exit, and gases are emitted at a minimum temperature of 200°C and a speed of around 30 metres per second to ensure adequate dispersion.

The combination of ESP and fabric filters is unusual as most waste to energy plants have one or the other system (modern plants almost invariably have the more effective fabric filters); however both are employed at this plant in order to meet the very strict standards relating to particulate emissions, which are more than three times more stringent than WID. SNCR systems are also usually preferred to SCR systems on economic grounds, however SCR is more effective and required at the plant to meet the stringent emission limit for NO_x.

Ash Handling and Processing

Bottom ash from the grate is collected and transferred via a conveyer to barges where it is transported via the River Seine to treatment centres in Isles-les-Meldeuses and Saint-Ouen-Alms for processing.

Fly ash from the ESP and fabric filter is collected in silos and treated prior to disposal in a hazardous landfill. The fabric filter cake residue is high in sodium compounds; sodium carbonate is recovered where possible. Remaining residues are then solidified by mixing with cement and special additives that help stabilise the pollutants. Rendered inert, they then go to class 1 (CET1) hazardous landfill for processing where they are stored in lined cells and listed to ensure their traceability.

Plant Performance

MSW Processed

The plant processes up to 460,000 tonnes per year of residual MSW from 22 communities in Paris.

Power and Heat Generation

The turbine generator has a rated output of 52MW, though this is only achievable when no steam is extracted for the district heating network. The theoretical gross electrical efficiency is 30% which is high; however the high level of steam extraction for district heating results in the average electrical efficiency being far lower than this in practice.

The following performance data is for 2011:

- 459,772 tonnes of waste throughput;
- 132,336 MWh of electricity;

- 87,684 MWh of electricity exported;
- 513,331 MWh of steam.

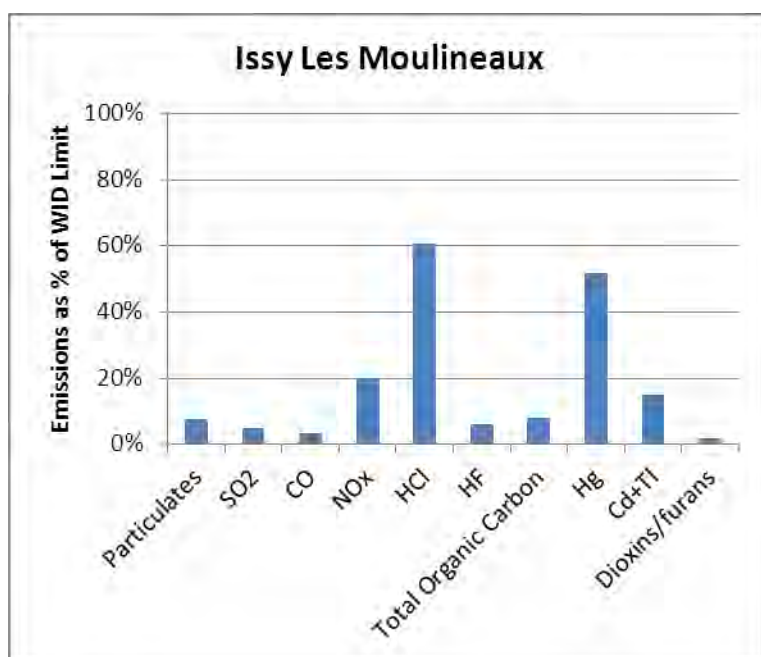
It has not been possible to accurately calculate the efficiency as no data is available on the actual waste calorific value, but this implies an annual average gross electrical efficiency around 10% and a thermal efficiency of around 40%. Despite the low electrical output the overall efficiency is therefore around 50%, which is much higher than a plant exporting only electricity would be capable of.

Environmental Performance

Emissions to Air

The plant has to comply with stricter emissions limits than others in France due to its urban location and to ensure compliance with future regulatory standards. Air emission performance is provided in the table below.

Figure 2-5-3: Emission limits for the ISSEANE plant in Paris for 2011



Source: WSP analysis of plant data

During operation of the plant, the following measures are carried out for different discharges:

- Continuous measurements of discharges into the Seine;
- Continuous measurements for gaseous emissions;
- Quarterly measures for heavy metals, dioxins and furans.

Data is made available to the public which includes all the above results. The plant has generally operated well below the emission limits throughout its operational life. A few, brief instances of exceedence have been

reported however (particularly for HCl), though there have been none to date in 2012. Reports covering the entire lifetime of the plant are available from TIRU's website²¹ (note in French only).

Odour emissions are avoided by extracting air from the tipping hall for use as combustion air, keeping the facility under negative pressure. This is a typical practice for modern waste to energy plants.

Emissions to Water

Process water effluent is discharged to sewer following treatment in an internal effluent treatment centre in order to meet discharge limits; there is no waste water discharge to the River Seine. Water abstracted from the River Seine for the condenser is returned to the river subject to temperature limits not being exceeded (maximum of 28°C). Water for cooling is used in an indirect system, so there is no contamination prior to discharge.

Emissions to Land

Ash is transferred from the WtE plant by barge, which helps avoid 5,200 vehicle movements per year which would be required were the material to be transferred by road. Bottom ash is recycled for use as an aggregate. Recovered metals are recycled and fly ash is treated prior to disposal in a hazardous landfill.

In 2011 the following tonnages of bottom ash and metals were produced:

- 85,583 tons of bottom ash;
- 7,226 tons of ferrous metals;
- 726 tons of nonferrous metals.

Footprint and Visual Impact

Visual impact was a key concern from the outset and the unique design reflects this; the plant is buried 31m below the ground and from street level it does not appear to be an industrial site, more closely resembling an office building which helps it blend in with the surrounding commercial and residential developments. The building stands only 21m above ground level (approximately equivalent to a 6 story building), and the two stacks protrude 5m above roof level and are well hidden.

The plant is clad in masonry and has a 'green roof'; heavy tree planting helps to mask the building and encourages biodiversity. There is no visual plume from the stacks as a result of the flue gas reheat system.

²¹ <http://www.tiru.fr/spip.php?article627&datetele=2011>

Figure 2-5-4: Photographs of the ISSEANE waste to energy plant



Source: Hitachi Zosen Inova

The plant footprint is relatively large however. The horizontal boiler reduces the height but increases the overall length and the addition of the recycling centre further increases the total area.

Operability, Reliability and Availability

Availability data for the plant could only be found for 2011, as follows:

- Line 1 – 79.4% (6955 hours);
- Line 2 – 81.2% (7113 hours).

This is a relatively low availability figure, though the reason for this is unknown.

WSP requested further data from the operator but none has been received by the time this report was finalised.

Economics

The total investment in the plant was €604 million. This cost does include the recycling centre and novel architecture and civil engineering challenge associated with locating the plant 31m below ground level. This is a very high capital cost for a plant of this size; of the order of 50% higher than may be expected for a more standard waste to energy plant without the structural, architectural and flue gas treatment enhancements.

The ISSEANE plant is a major feat of engineering. The plant is sunk about 30 metres into the bank of the River Seine with all the associated hydrogeological challenges of building the plant there. The exhaust gas chimneys protrude only 5 metres above the building but in order to do this the plant has had to guarantee emission limits to air of 50% of the WID values for all pollutants. It is truly a state-of-the-art WtE facility.

Case Study 6 – Reno Nord, Aalborg, Denmark

Overview

The Energy from Waste facility at Aalborg, Denmark is owned and operated by Interessentskabet Reno-Nord (I/S Reno-Nord) which is a Danish municipal authority jointly owned by seven municipalities in North Jutland. It is responsible for handling the waste streams produced by 225,000 residents of the seven municipalities.

Lines 1 and 2 were built by the company between 1978 and 1980 and consisted of two Vølund rotary kiln furnace systems, each of which had a capacity of 8 tonnes of waste per hour. The plant supplied thermal energy to the district heating system of Aalborg Fjernvarmforsyning, the municipal utility company.

In 1989 I/S Reno-Nord and I/S Nordkraft, the local electricity supplier established a joint venture for the construction of a waste fired combined heat and power plant. The new waste incineration line (line 3) was put into service in 1991, had a throughput of 12.5 tonnes per hour and provides energy for electricity generation and heating. Line 3 is fitted with a Babcock and Wilcox Vølund BS-W combustion grate.

In 1999 the governing board of I/S Reno-Nord decided to build a new incinerator line (line 4) for combined heat and power (CHP) generation with a rated throughput of 20 tonnes of waste per hour with a lower calorific value of 12 MJ/kg and an annual waste tonnage of 160,000 tonnes. Line 4 utilises a Babcock and Wilcox Vølund air-cooled DynaGrate which was designed to have sufficient capacity to burn the entire medium term volume of waste produced by the seven municipalities. The new system was designed to significantly improve upon the applicable statutory requirements and to use the latent energy of the waste significantly more efficiently.

Line 4 can supply approximately 18MW of electricity which is fed into the main electricity grid. Furthermore, the plant will supply approximately 43 MW of heat to the district heating network of Aalborg. The energy produced will supply approximately 16,000 houses with electricity and approximately 30,000 houses with district heating.

With the commissioning of line 4, lines 1 and 2 were decommissioned, line 3 remained in operation.

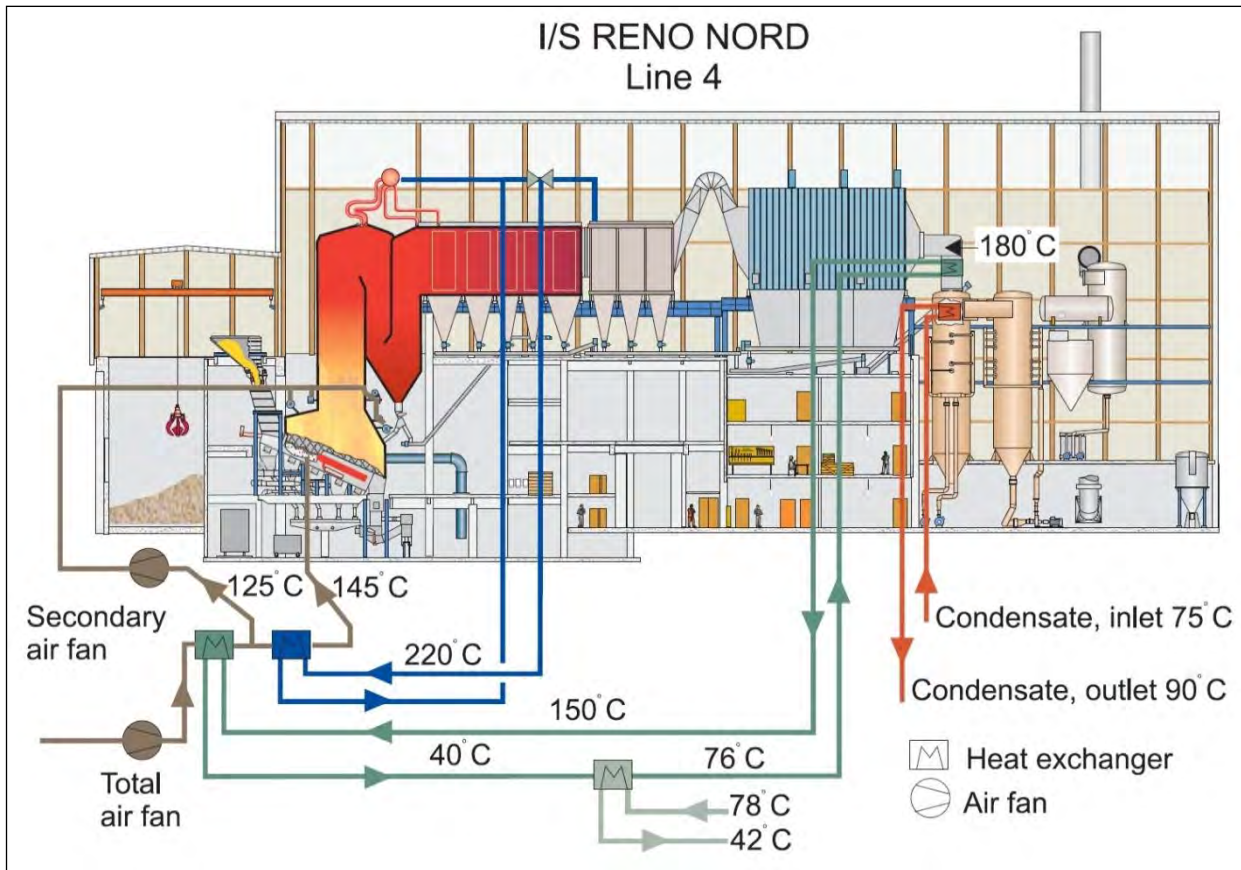
According to literature supplied by Babcock and Wilcox Vølund, line 4's power and energy generation levels are as follows:

| | |
|--|-----------------|
| Electricity (gross) | 17,918 kW |
| Heat from district-heating condensers | 43,412 kW |
| Condensation heat from the flue gas cleaning system | 4,000 kW |
| Condensation heat with the current district heating water return temperature | 7,000 kW (max.) |
| Resulting gross electrical efficiency | 27% |
| Resulting overall thermal efficiency | 98% |
| Boiler efficiency | 92% |

The Process

The process Reno-Nord line 4 is summarised below:

Figure 2-6-1: Process schematic for the Reno Nord waste to energy plant



(Source: BWV Combustion Technology for Generating Energy from Waste – Case Study: Reno Nord, Line 4 A High-Efficiency Waste Incineration Plant)

Line 4 is fitted with a Babcock and Wilcox Vølund BS-W Mark 5 air-cooled grate which is suitable for conversion to water cooling in desired in the future.

The steam generated from the incineration line is passed to a CHP system that was supplied by B+V Industrietechnik GmbH. The turbine is rated at 17,918 kW.

Table 2-6-1: The technical data for Line 4 of the Reno Nord plant

| | | |
|-----------------------|------------------------|-----------------------|
| Waste silo | Capacity | 12,500 m ³ |
| | Number of dumping bays | 5 |
| Waste handling cranes | Quantity | 2 |
| | Grab volume | 8 m ³ |
| | Type | Fully automatic |

| | | |
|----------------------------|---------------------------|---|
| | Supplier | Kone Cranes |
| Combustion System | Throughput | 20 t/h |
| | Grate type | BS-W, air cooled |
| | Grate length | 9.9 m |
| | Grate width | 9.1 m (usable width 8.8 m) |
| | Supplier | Babcock & Wilcox Vølund A/S |
| Boiler | Boiler wall protection | Inconel / refractory |
| | Burners | Oil, 2x 25 MW |
| | Thermal energy input | 66.7 MW |
| | Steam generation | 22.2 kg/s |
| | Steam pressure: | 50 bar (a) |
| | Steam temperature: | 425 °C |
| | NO _x reduction | SNCR |
| | Supplier | Babcock & Wilcox Vølund A/S |
| Turbine/generator | Output | 17.9 MW |
| | Temperature / pressure | 422 °C / 48 bar |
| | Supplier | B+V Industrietechnik GmbH |
| District heating condenser | Output | 43 MJ/s |
| | Temperature | 38 °C / 78 °C |
| | Supplier | B+V Industrietechnik GmbH |
| Dust removal | Type | Electrostatic filter |
| | Number of fields | 3 |
| | Capacity | Less than 10 mg/Nm ³ |
| | Manufacturer | Alstom |
| | Supplier | Babcock & Wilcox Vølund A/S |
| Flue gas cleaning | Flow | 112,000 Nm ³ /h |
| | Type | Wet flue gas cleaning |
| | Components | Quencher, acid scrubber, limestone-based alkali scrubber, HOK-based dioxin scrubber, venturi scrubber with agglomeration filter, exhaust blower |
| | Condensation stage | Direct cooling with district heating water Heat generation for district heating: 4 MJ/s |
| | Supplier | LAB S.A. |
| MSR system | Manufacturer | ABB |
| | Supplier | Babcock & Wilcox Vølund A/S |

| | | |
|----------|------------------------|-----------------|
| Chimney | Height | 75 m |
| Building | Dimensions (L x W x H) | 115 x 25 x 45 m |

Source: BWV Combustion Technology for Generating Energy from Waste – Case Study: Reno Nord, Line 4 A High-Efficiency Waste Incineration Plant

Waste reception, storage and feeding

Reno-Nord receives approximately 250 loads of waste per day which is weighed electronically on a weighbridge. A random selection of loads is selected by the IT system or in accordance with guidelines from the municipalities or Reno-Nord business management. The selection process is completely independent of the road booth staff.

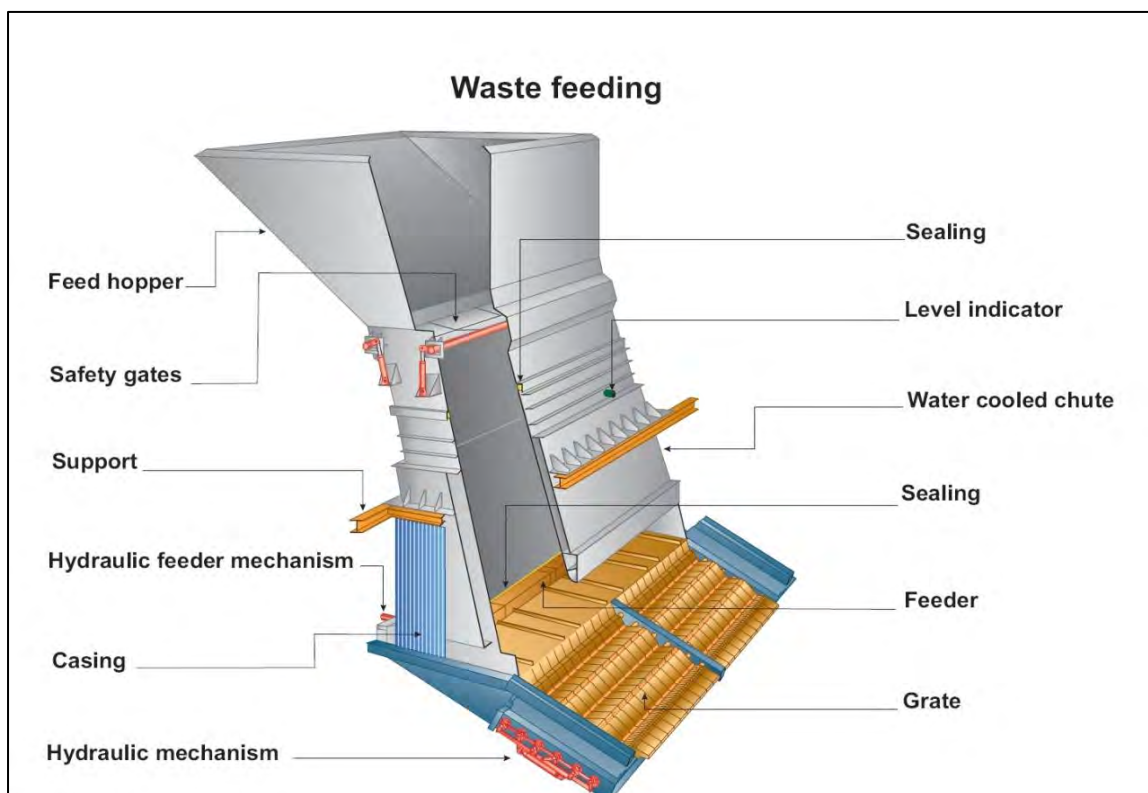
Loads selected for inspection are routed to a specific area where the load is tipped and checked either by Reno-Nord's own staff or by supervisory staff from the municipalities. Waste loads that are not selected for random inspection are discharged into the main waste silo via one of five specific tipping points.

Two fully automated cranes with a grab capacity of 8m³ each are used to feed each of the combustion lines to achieve stable combustion and energy generation.

The feed rate must be constantly and continuously adapted to the transport capacity of the grate in order to obtain a uniformly distributed layer of fuel on the grate, and thus achieve uniform energy generation.

The feed system in the Reno-Nord plant is designed to avoid blockages in order to ensure continuous inflow of waste to the water-cooled feed chute. Three sides of the hopper are vertical to prevent the formation of bridges in the waste material in the hopper.

Figure 2-6-2: The waste feeding system



Source: BWV Combustion Technology for Generating Energy from Waste – Case Study: Reno Nord, Line 4 - A High-Efficiency Waste Incineration Plant

The inner surfaces of the hopper are lined with sheet steel wear panels.

There are two hydraulically actuated safety hatches between the hopper and the chute. These hatches close automatically if there is an electrical power failure.

The chute carries the waste from the feed hopper to the waste feeder and also acts as a storage area for the waste prior to it being fed onto the grate. The chute is constructed from thick steel plate with water cooling in order to withstanding the effects of extreme heating. The heat extracted by chute cooling water is fed to the district heating system.

The chute is attached to the combustion chamber and is shaped like a funnel with its wide end facing the combustion chamber which prevents waste from getting stuck.

The waste is fed to the grate by a hydraulic waste feeder at a variable speed corresponding to the energy generation levels which results in a consistent, continuous flow of waste supplied to the grate. Each ram is air-cooled with two cooling air inlets.

Combustion

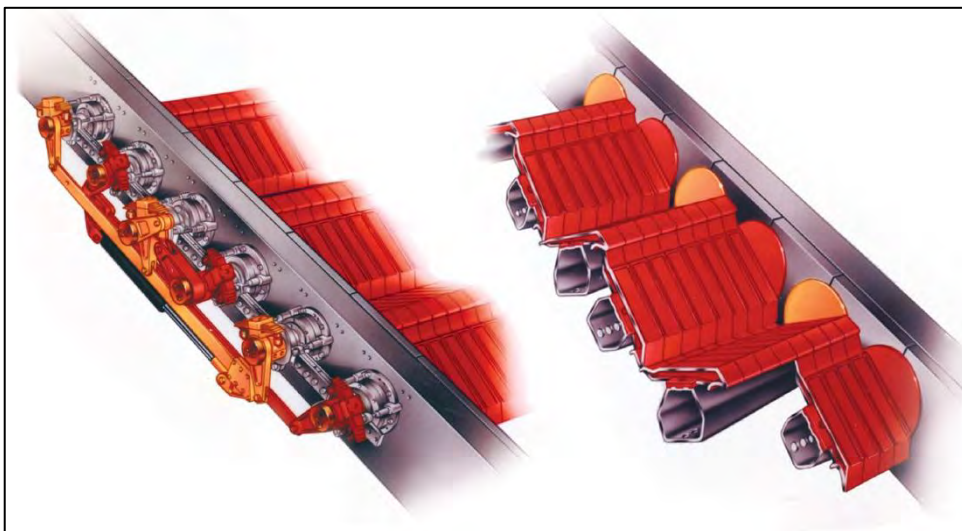
The Reno-Nord line 4 utilises a Babcock and Wilcox Vølund BS-W mark 5 air cooled combustion grate which is consists of two parallel grates lanes, each with a width of 4.4m.

The BS-W grate system can handle all types of unsorted solid waste and can be used for combined fuelling with biomass.

The grates resemble a set of stairs and the individual grate bars are arranged in alternating horizontal and vertical orientation. The grates bars are in turn fitted to shafts so the bars of two adjoining shafts can join to yield a continuous grate surface.

The structure of the grate is shown below:

Figure 2-6-3: The design of the grate used in the Reno Nord plant



Source: BWV Combustion Technology for Generating Energy from Waste – Case Study: Reno Nord, Line 4 A High-Efficiency Waste Incineration Plant

When the shafts rotate 60 degrees in opposite directions the orientation of the grate elements changes between horizontal and vertical. The alternating orientation of the elements from horizontal to vertical creates a wave-like motion in the lengthwise direction. This motion optimises the mixing and distribution of the waste on the grate bed to ensure proper drying, transport and combustion.

The drive mechanism which is located outside the combustion chamber, allows a gap of 2mm to form between the grate bars of adjoining shafts while the grate is moving, and the combustion air is fed through the gaps. The grate motion keeps the air gaps clean and from particulate matter.

The entire volume of combustion air is drawn equally from the waste bunker and the boiler house by a total air fan. The fan is controlled by a variable frequency drive and the air is routed to an air pre-heater consisting of two sections. The entire volume of combustion air is heated to 125°C in the first section of the air pre-heater and then further heated to 145°C in the second section by a partial feedwater stream tapped off from the water emerging from the economiser.

After emerging from the air preheater, the primary air is distributed by a duct system to the individual hoppers under each grate section. The air volume is measured using venture tubes and fed to the individual grate sections via the control dampers in the individual supply ducts. These dampers are controlled by the combustion controller so the air supply to the individual grate sections can be controlled independently.

Secondary air is injected into the combustion zone in multiple locations and with varying velocities.

Energy Production

The boiler for line 4 is built as a four-pass boiler with three radiant passes and a horizontal convection pass, consisting of an evaporation tube bank, superheater and economisers. The steam data was specified to be the same as line 3 as shown below:

- Steam generation: 80 tonnes per hour;
- Steam pressure: 50 bar (a);
- Steam temperature: 425°C;
- Feedwater temperature: 130°C.

The turbine system was supplied by B+V Industrietechnik GmbH. The turbine is designed for a swallowing capacity of 120% of the nominal steam generation. The rated power of the generator is 17.918 MW. The turbine is fitted with a bypass system for the full volume of steam.

The turbine is equipped with uncontrolled steam extraction for condensate preheating via a heat exchanger and an uncontrolled extraction for heating the feedwater tank.

The condensate is preheated in two stages. The first preheating stage uses heat from the second stage of the flue gas cooler. Following this, the condensate is further heated by extracted steam in a separate heat exchanger before being pumped back into the feedwater tank, where it is maintained at a temperature of 130°C.

The following data has been provided by Babcock and Wilcox Vølund:

- The plant converts 97% of the wastes energy;
- 27% electricity efficiency;
- 18 MW of electricity;
- 43 MW of heat to the Aalborg district heating system.

Air Pollution Control

The first stage of the flue gas cleaning system consists of a three-field electrostatic filter supplied by Alstom. The dust concentration after the filter is in the order of 10 mg/Nm³ with a flue gas oxygen content of 11% by volume (dry). The low dust volume arises from the fact that the dust concentration at the inlet to the scrubber must be kept as low as possible due to regulations regarding the introduction of heavy metals into wastewater.

The electrostatic filter is followed by a wet flue gas cleaning system supplied by LAB S.A.

This flue gas cleaning system employs a unique process to remove ammonia, hydrogen chloride, sulphur dioxide, hydrogen fluoride, mercury, heavy metals, dioxins and solid particles from the flue gases of waste to energy plants. The flue gas cleaning system also includes an ammonia stripper to remove ammonia from the wastewater before it is fed to the wastewater treatment plant. The stripper was supplied by Rauschert Verfahrenstechnik GmbH.

Principal components of the flue gas cleaning system:

- The first stage is an open spray scrubber. Here the flue gas is cooled to approximately 90°C by a water spray at the inlet of the scrubber. The primary components removed in the first stage are ammonia, hydrogen chloride, and mercury. Limestone slurry is used as the active medium;
- The second stage is also an open spray scrubber, which primarily serves to remove sulphur dioxide. Limestone slurry is used as the active medium;
- The third stage consists of two parts: an open part equipped with the patented LAB G nozzles, and a second part with a filling of solids. This stage is intended to remove dioxins and furans. It uses the patented Dedioxlab wet catalyst process.

In order to extract energy from the flue gas and condense the water vapour in the flue gas, the water circuit of the scrubber includes a heat exchanger that transfers the energy in the process water to the district heating network.

Sodium hydroxide is added in the third stage. It enables a quick response to sulphur dioxide peaks and simplifies any adjustments that may be necessary. Hearth furnace coke is injected in the third section to remove dioxins and furans.

- The fourth stage consists of the agglomeration filtration modules (AFMs), which remove the remaining dust particles;
- This is followed by the wastewater treatment plant and ammonia stripper, which removes the ammonia emissions washed out of the flue gas;
- The limestone silo and the limestone pre-treatment system;
- The gypsum handling system;
- The storage container for hearth furnace coke, the pre-treatment system and the spray injection system.

Ash Handling and Processing

As result of the incineration process approximately 25% of the waste incinerated at Reno-Nord becomes bottom ash and is composed of 98% inorganic material and approximately 2% is non-combusted organic material.

The bottom ash is then further processed to separate the ferrous and non-ferrous metal from the mineral fractions. The ferrous and non-ferrous metals are recycled and the mineral fractions can be used for sub-base layers in road buildings, paths and foundations.

Reno-Nord conditions for reuse of bottom ash are as follows:

- Assistance to contractors and builders in connection with the preparation of the review and any exemption application to the municipality;
- Delivery of slag directly on site at no cost to the client within Reno-Nord partner municipalities;
- Payment of £ 35.00 per tonne to cover part of the cost of deploying the necessary environmental measures, ie asphalt, laying of membrane or other requirements for approval of the project.

Plant Performance

MSW Processed

Reno-Nord line 4 has a maximum capacity of 160,000 per annum (approximately 480 tonnes per day assuming 8,000 hours of operation) with a minimum calorific value of 12 MJ/kg. The residual waste treated at Reno-Nord has been collected from the seven municipalities in Aalborg.

All waste is transported to the facility using refuse collection vehicles.

Power and Heat Generation

Line 4 generates the following power and heat outputs:

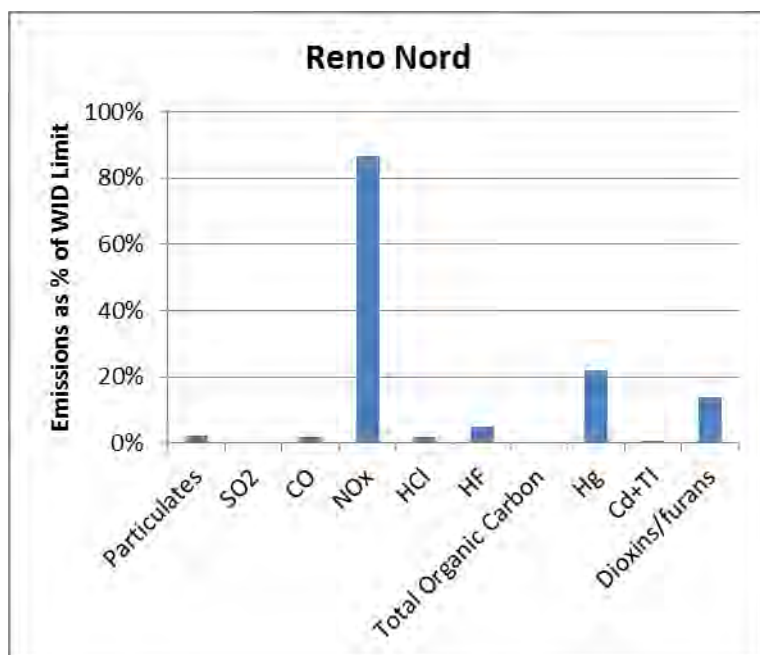
- 18 MW of electricity
- 43 MW of heat to the Aalborg district heating system

Environmental Performance

Emissions to Air

As described in the Air Pollution Control section above the emissions to air are minimised through a combination of high efficiency combustion within the furnace/boiler as well as by an efficient flue gas cleaning system. All emissions are normalised to conditions of 1 atmosphere pressure, 25°C and 11% O₂.

Table 2-6-2: Emission limits for the Reno Nord plant in Aalborg for 2011



Source: Grønt regnskab 2011 – Reno Nord

Emissions to Water

Reno Nord reported the following waste water data:

Table 2-6-3: Waste water emissions from the plant

| Waste Water | | 2007 | 2008 | 2009 | 2010 | 2011 |
|-----------------------------|----------------|--------|--------|--------|--------|--------|
| Waste Water to Public Sewer | m ³ | 16,874 | 12,661 | 11,330 | 13,647 | 5,911 |
| Waste Water to Limfjord | m ³ | 35,293 | 41,688 | 38,818 | 39,595 | 46,697 |

Source: Grønt regnskab 2011 – Reno Nord

Emissions to Land

As result of the incineration process approximately 25% of the waste incinerated at Reno-Nord becomes bottom ash and is composed of 98% inorganic material and approximately 2% is non-combusted organic material.

Ferrous and non-ferrous metals are removed from the bottom ash for recycling and the remaining mineral material is processed into aggregate for use in the construction industry. The use of bottom ash as an aggregate was approved by the Ministry of the Environment on the 21st January 2010, which allows the use of residues and soil for construction works and the use of sorted, uncontaminated construction waste as a construction material. Specific guidance and restrictions have also been published.

Provided below is a summary of the outgoing volumes of materials from Reno Nord:

Table 2-6-4: Discharges from the Reno Nord plant

| Material | | 2007 | 2008 | 2009 | 2010 | 2011 |
|-----------------------------|------|--------|--------|--------|--------|--------|
| Bottom Ash (Slag) | tons | 35,119 | 23,670 | 48,314 | 12,614 | 30,132 |
| Combustion Iron | tons | 2,277 | 2,753 | 2,377 | 1,462 | 2,223 |
| Non-Magnetic Metals | tons | 483 | 753 | 549 | 278 | 695 |
| Iron and Scrap Metal | tons | 10 | 35 | 47 | 29 | 0 |
| Plastics for their Reuse | kg | 600 | 270 | 240 | 540 | 0 |
| Paper | kg | 142 | 1,114 | 3,325 | 4,025 | 4,650 |
| Fly Ash | tons | 2,274 | 2,616 | 2,902 | 1,862 | 2,921 |
| Filter Cake | tons | 415 | 271 | 242 | 196 | 357 |
| Gypsum | tons | 104 | 249 | 323 | 126 | 201 |
| Residue from Semi Dry Plant | tons | 162 | 0 | 247 | 931 | 0 |

Source: Grønt regnskab 2011 – Reno Nord

Footprint and Visual Impact

Figure 2-6-4: Photograph of the Reno Nord waste to energy plant in Aalborg



Source: Babcock & Wilcox Vølund

Operability, Reliability and Availability

Table 2-6-5: Technical data for Reno Nord

| Description | Lines 1 and 2 | Comment |
|---------------------------------------|---------------|------------------------|
| Time Available | ~8,000 hours | Based on 2005/6 Period |
| Electricity | 17,918kW | |
| Heat from District Heating Condensers | 43,412kW | |
| Electrical Efficiency | 27% | |
| Thermal Efficiency | 98% | |
| Boiler Efficiency | 92% | |

(Source: BWV Combustion Technology for Generating Energy from Waste – Case Study: Reno Nord, Line 4 - A High-Efficiency Waste Incineration Plant)

Based on data provided by Babcock & Wilcox Vølund the process is >40% efficient. It is higher than a conventional plant because part of the export is heat for district heating (CHP mode).

Economics

The following tariffs for combustion have been published by Reno-Nord for 2012:

Table 2-6-6: Waste treatment cost

| Description | Rate / Tonne (Danish Krone) | Rate / Tonne (Aus Dollar) * |
|--|--------------------------------|--------------------------------|
| Refuse | 598.00 | 99.15 |
| Bulky waste / Waste recycling centres | 410.00 | 67.98 |
| Industrial waste | 410.00 | 67.98 |
| Special waste | 665.00 | 110.26 |
| Instant combustion – Must be packed in boxes | 665.00 | 110.26 |
| Surcharge per box – max 300kg in each box | 60.00 / pc. | 9.95 |
| * Exchange Rate dated 28 th September 2012. | | |

Source: Reno Nord website -

http://translate.google.co.uk/translate?hl=en&sl=da&u=http://www.renonord.dk/&prev=/search%3Fq%3Dreno%2Bnord%26hl%3Den%26biw%3D1366%26bih%3D566%26prmd%3Dimvnso&sa=X&ei=ZEplUJuVFka_0QXWsoGwBg&ved=0CCMQ7gEwAA

The Reno Nord plant is a state-of-the-art example of a waste processing facility that delivers hot water into the district heating network of the area. The electrical conversion efficiency is 27% but the combination of that with the heat utilisation means the total efficiency of the plant is >40%.

Case Study 7 – Energos, Sarpsborg, Norway

Overview

Energos are a leading European supplier of waste gasification systems. The Energos process is fully proven with eight operating plants in Norway (6), Germany (1) and the UK (1).

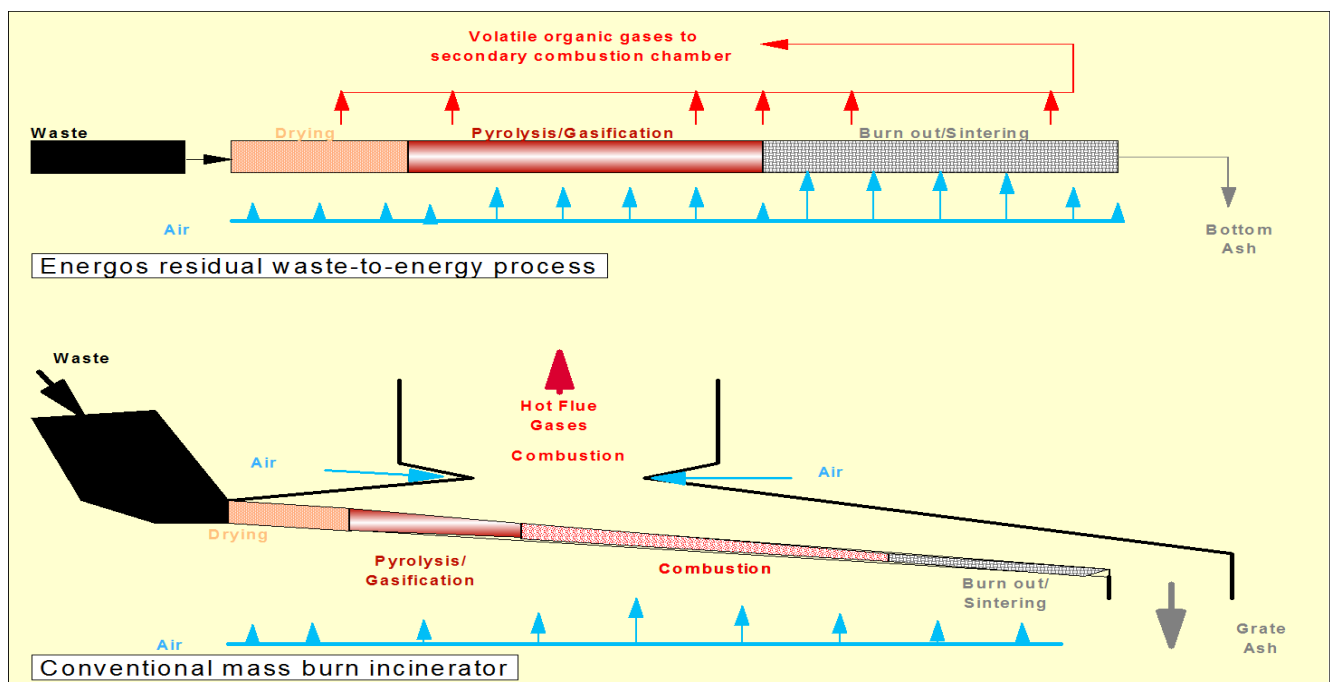
The Sarpsborg II plant is the most recently constructed Energos plant, and was commissioned in 2010 to supply steam to Borregaard Industries biorefinery in Sarpsborg, Norway. This is the second double line gasification plant to be built at the complex following the original plant (Sarpsborg I) which was commissioned in 2002. The Sarpsborg II plant processes 78,000 tonnes per year of residual commercial and industrial waste, which is converted into syngas in the gasifier before being combusted to raise steam. The steam is then sent 'over the fence' to the adjacent industrial complex where it is used for process heating purposes, displacing fuel oil which would otherwise need to be used to raise steam. The plant is owned and operated by Hafslund ASA, a Norwegian power company.

The plant does not produce electricity as all steam is consumed by the biorefinery. The use of steam in this manner results in a very high thermal efficiency.

The Process

The plant consists of two identical gasification lines each capable of processing 39,000 tonnes of waste per year. Each line incorporates a two-stage thermal reactor consisting of a primary gasification zone and a secondary thermal oxidation (combustion) chamber. This process is referred to as 'close-coupled gasification' or 'staged combustion' as the syngas produced is immediately combusted to raise steam in a conventional steam cycle as opposed to being used directly in gas engines or converted to higher fuels or chemicals.

Figure 2-7-1: Schematic of the Energos two stage process

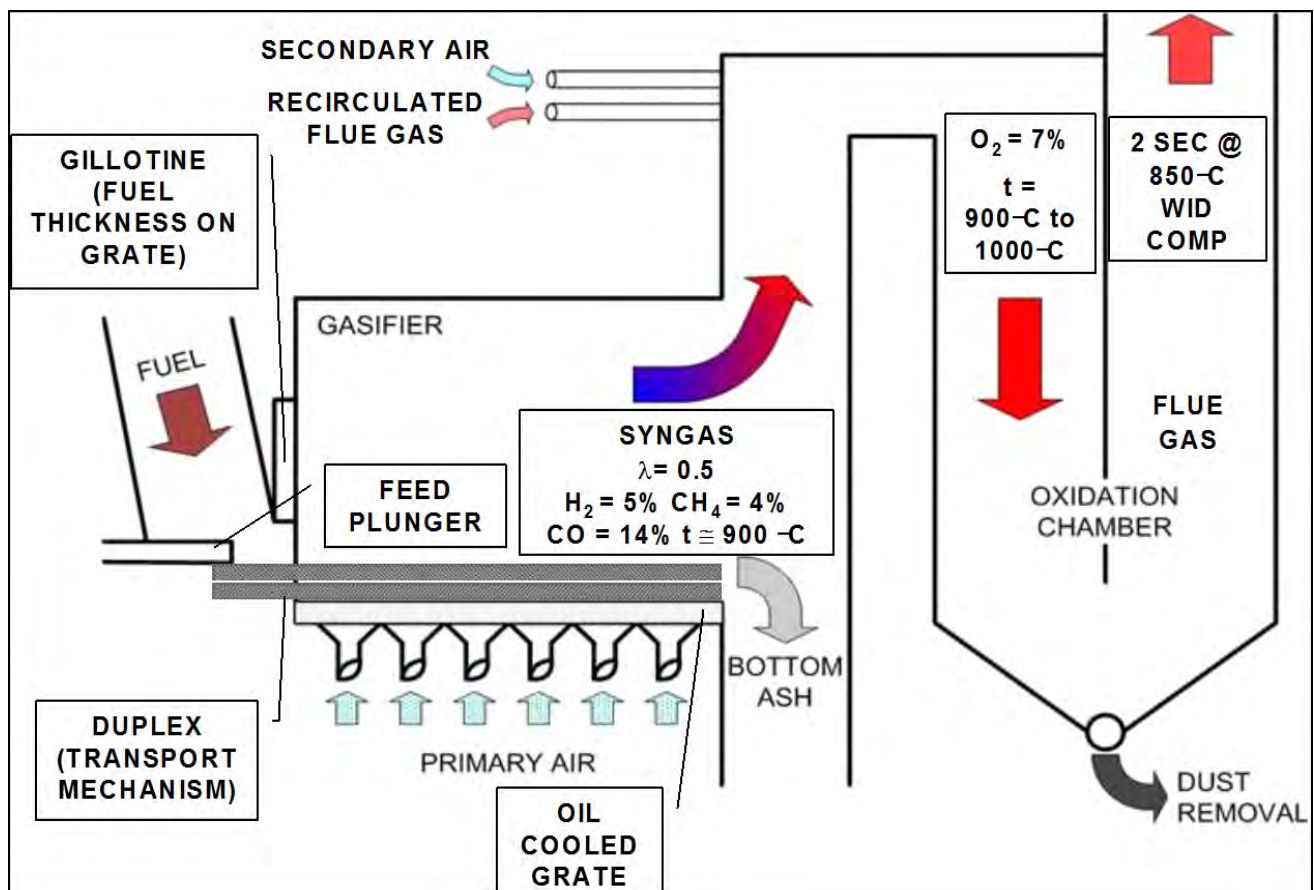


In the gasification zone waste is heated in a starved-air environment (approximately half the stoichiometric requirement) to produce a syngas comprising primarily of carbon monoxide, hydrogen, methane and carbon dioxide. The syngas then passes to the thermal oxidation chamber where it is immediately combusted, and the hot flue gases then pass to a boiler to raise steam. The exhaust (flue) gases are then cleaned to a level sufficient to comply with Norwegian emissions limits prior to discharge to atmosphere.

The two-stage design seeks to utilise the benefits of gasification to produce a syngas whilst ensuring sufficient oxygen is added at the end of the primary zone to achieve the required carbon burn out of the ash. The syngas flows through 180 degrees where staged oxidation takes place as a result of the injection of air and recycled flue gas via multiple injection points.

Some commentators would argue the two-stage gasification/combustion process is effectively incineration but Energos has convinced Ofgem (the UK regulator) that their process should be classified as gasification by measuring the syngas composition and CV between the primary gasification stage and secondary combustion stage, demonstrating that the process is operating as a gasifier with a clear distinction between the gasification and combustion stages. The company has developed a second generation design where the secondary combustion stage is separated from the primary gasification stage. this design has been employed at the Isle of Wight facility in the UK.

Figure 2-7-2: The second generation Energos design



Source: Energos

Waste reception, storage and feeding

Waste is delivered to the plant by road and tipped into the waste bunker. The plant has a pre-treatment system including a shredder with belt conveyors and a magnetic belt for metal separation. An automatic overhead

crane system feeds the shredder. The magnetic metal will be extracted from the shredded waste and transferred to containers. Shredded waste is unloaded in the fuel bunker.

Fuel is transferred from the fuel bunker by use of the overhead crane and unloaded into hoppers upstream the feeding chamber of each gasification chamber. The fuel mixture is fed from the feeding chamber into the gasification chamber.

Combustion

The primary gasification reactor incorporates a fixed horizontal oil-cooled grate that is divided into several separate sections, each with its own air supply. A water-cooled guillotine is installed at the inlet to the gasification chamber to control the thickness of the fuel bed. Waste is transported along the grate by the duplex, which is hydraulically operated and water-cooled.

The syngas produced in the gasification reactor passes into the combustion chamber where it mixes with air and recirculated flue gas for NO_x control via various nozzles positioned strategically in the oxidation chamber. This ensures complete oxidation of the syngas and close temperature control within the combustion chamber.

The control of the combustion process has been developed to a high level ensuring that the gas phase emissions of the major pollutants are at very low levels without the need for a complex range of gas cleaning processes. Careful control of the air flows to the primary and secondary combustion zones is critical to successful operation and minimisation of pollutant emissions.

Figure 2-7-3: Inside the Sarpsborg II plant



Source: Energos

Energy Production

The hot flue gases pass to a Heat Recovery Steam Generator (HRSG) where the sensible heat is used to produce steam. Each HRSG is a combined smoke-tube and water-tube design with an economiser. The water-tube section of the boiler comprises the evaporator and superheater elements of the boiler which are designed

to facilitate easy removal for inspection and maintenance. The smoke-tube part of the boiler is mounted in a vertical configuration and employs a continuous cleaning process.

Unlike the majority of WtE plants the Sarpsborg II facility does not generate electricity, rather all steam produced is piped to the Borregaard Industries biorefinery where it is used for process heating.

The parameters of each HRSG are as follows:

- Steam pressure – 23 bar;
- Steam outlet temperature - 217°C;
- Feed water inlet temperature - 105°C;
- Nominal HRSG capacity - 16.4 MW.

Air Pollution Control

The plant must comply with Norwegian emissions limits (which are broadly in line with those in the EU Waste Incineration Directive).

The decoupling of the gasification and oxidation steps allows tighter control over combustion than can be achieved in conventional energy from waste plants which can result in good emissions performance though flue gas cleaning is still necessary.

The plant is supplied with a semi dry flue gas cleaning system located downstream of each HRSG. The flue gas cleaning system consists of adsorbent silo, baghouse filter and storage silo for filter dust. The cleaning of the flue gas is based on injection of adsorbent (lime and carbon) into the flue gas for absorption of acid components, adsorption of heavy metals, mercury, TOC and dioxins. Steam is injected into the flue gas prior to the injection of lime and carbon to achieve the correct relative humidity.

Fly ash and adsorbents are separated from the flue gas in a baghouse filter. Residue from the filter is collected and pneumatically transported to the filter dust storage silo. The silo is drained at regular intervals through a sealed system into designated trucks for transport to disposal in accordance with statutory regulations.

The controlled combustion in the thermal oxidation zone minimises NO_x formation and the plant is able to comply with emissions limits without any form of NO_x control (such as SCR or SNCR systems which are typically used on WtE plants).

The flue gas fan is located downstream of each baghouse filter. The flue gas fans maintain the required draft in the gasification and high temperature oxidation chambers and discharge the flue gas to the atmosphere via a common stack. A portion of the flue gas is recycled to the high temperature oxidation chamber by use of a re-circulated flue gas fan.

Ash Handling and Processing

The bottom ash is approximately 21% of the input waste feed by weight. The bottom ash is discharged from the gasification chamber at the end of the grate where it is cooled in a water-basin and transported to the outdoor bottom ash storage. Currently the ash is deposited in a landfill, although alternatives may be found in the future. The ash quality produced from Energos plants has been demonstrated to meet the requirements for use in aggregates, but no commercial market is available at Sarpsborg.

The APC residue is approximately 7% of the input waste feed by weight. This figure is relatively high, primarily as a consequence of the high sulphur content of the waste. Energos advise that other plants of theirs have achieved filter residue volumes of 3 - 4% of the feed.

Plant Performance

MSW Processed

The plant processes 78,000 tonnes of residual commercial and industrial waste per year. The combined waste handling capacity of Sarpsborg I and II is 156,000 tonnes per year.

Power and Heat Generation

The plant has a thermal capacity of 32MW, and produces up to 250 GWh of steam per year. This is sufficient to offset approximately 24,000 tonnes of heavy fuel oil per year which were previously consumed. The overall efficiency of the process is in excess of 80%, much greater than would be possible if generating electricity.

The R1 efficiency (according to Directive 2008/98/EC Annex II) is 0.92, well in excess of the value of 0.65 required for the facility to be classed as a 'recovery' operation.

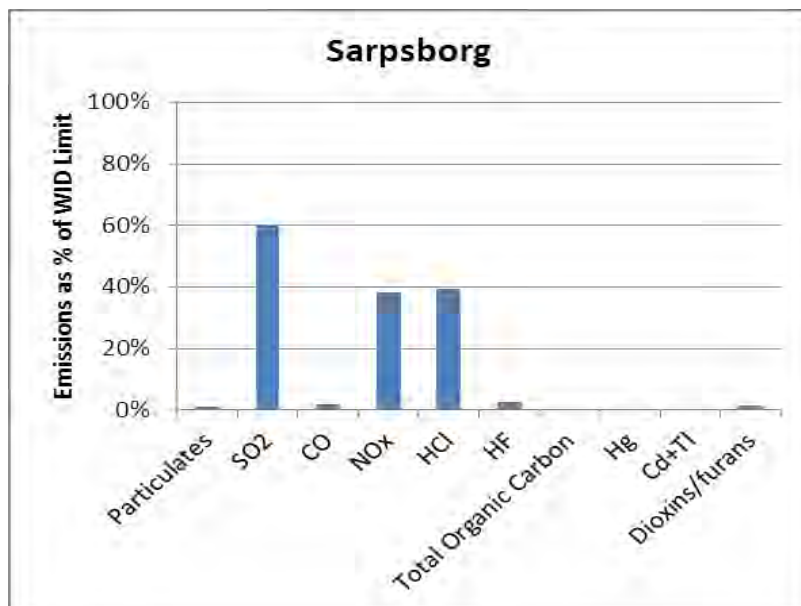
Environmental Performance

Emissions to Air

The Sarpsborg II plant has demonstrated very low emissions, well below the legislative limits. Energos state that dioxin levels are typically around 1% of the allowable limit and NO_x levels within 25% of the limits without any form of NO_x control. However, the plant has produced relatively high levels of SO₂ owing to high levels of gypsum in the input feedstock

The figure below shows the results of independent emissions testing (December 2010). However Energos do not publish emissions performance data online, so it has not been possible to obtain recent figures or verify that the emissions have been compliant over the entire operational history of the plant.

Figure 2-7-4: Emission values reported from Sarpsborg II for December 2010



Source: WSP analysis of Energos data

Odour in the vicinity of the plant is avoided by using air from the bunker hall as process air for the gasification and high temperature oxidation process.

Emissions to Water

No information on emissions to water could be obtained.

Emissions to Land

Ash from the plant is currently disposed of to landfill. No economically viable alternative uses for the bottom ash have been identified.

Footprint and Visual Impact

The location of the plant next to a biorefinery helps to minimise the visual impact as the surrounding area is heavily industrialised. The building has a footprint of 3,800m².

Figure 2-7-5: View of the Sarpsborg II plant



Source: Energos

Operability, Reliability and Availability

The plant has been operational for two years, and it understood to have performed well to date. In the first year of operation the first line recorded 7,591 hours (87%) and the second line recorded 7,305 hours (83%). This is a good availability for a plant in the first year, though this is not necessarily a good indicator of long term performance.

However, we understand there have been some issues relating to the relatively poor quality of the waste feedstock. High levels of plasterboard from demolition waste have resulted in relatively high SO₂ levels in the flue gas. The volumes of ash are also relatively high compared to plants operating on MSW, again due to the feedstock composition.

Economics

The plant is owned and operated by Hafslund Varme AS. The entire project cost approximately £45M. The M&E package cost approximately £30M, and the plant was balance sheet funded.

The two stage gasification/combustion process developed by Energos has been accepted as a gasification process by the UK regulator, Ofgem and Energos has received ROC's at the Isle of Wight facility.

Most of the existing reference plants supply steam 'over-the-fence' to a heat customer and so the low steam conditions (pressure and temperature) are not an issue. For a plant required to produce electricity only steam conditions of 40 bar and 400°C would be required.

The process is supplied in 40,000 tonne per year modules which can be built in parallel line to increase the required throughput capacity to 80,000 or 120,000 tonnes per year.

Case Study 8 – Zabalgarbi, Bilbao, Spain

Overview

The Zabalgarbi waste to energy plant near Bilbao is a conventional grate incinerator with an advanced energy recovery system. The WtE plant is combined with a natural gas fired power plant; steam produced by the waste heat recovery boiler is used within a Combined Cycle Gas Turbine (CCGT) process, resulting in a considerably higher electrical efficiency than would be possible in a conventional WtE plant. However, the increased efficiency is possible due to the external superheating of the steam to temperatures beyond that possible in a conventional plant.

The WtE plant consists of a single combustion line rated at 30 tonnes per hour, capable of treating up to approximately 250,000 tonnes of MSW per year. The CCGT plant consists of a 43MW_e gas turbine fired on natural gas and a 56MW steam turbine. Steam is raised from the combustion of MSW, and then the hot exhaust gases from the gas turbine are used to raise the temperature of the steam well in excess of what would be possible in a standard steam cycle. This enables a higher electrical output, produced with greater efficiency. The total net electrical output of the plant is approximately 95MW_e.

The plant was commissioned in 2004 and is owned and operated by Zabalgarbi S.A, a public-private partnership established specifically for the purpose of running the facility. A second line has been planned for some time, but development has not yet commenced. The plant is located on a large site on a hillside in the Bizkaia area to the south west of Bilbao.

Figure 2-8-1: The Bilbao waste to energy facility



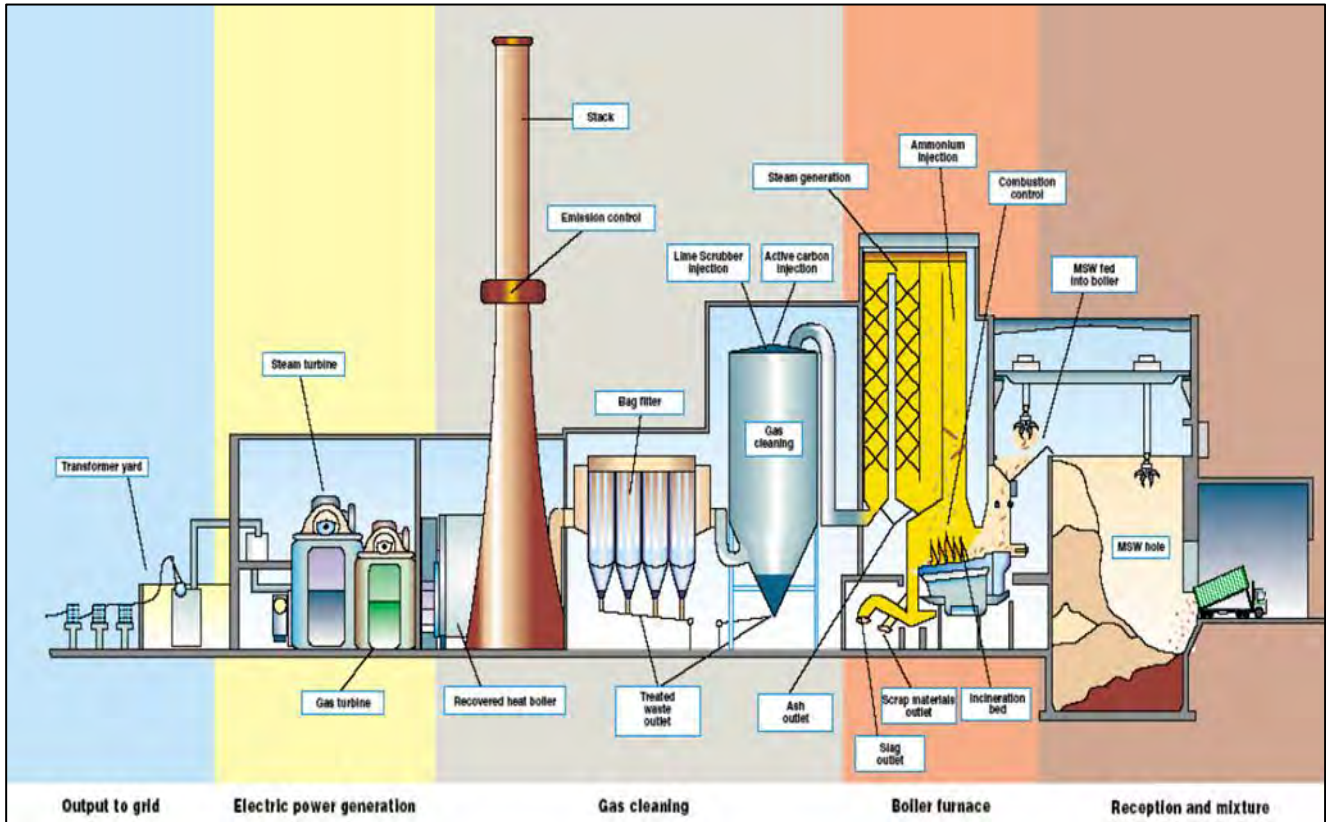
Source: Martin GmbH

The Process

The Zabalgarbi plant is a conventional grate incinerator supplied by Martin GmbH, but with a novel energy recovery system whereby the steam generated in the boiler is used as an input to a combined cycle gas turbine plant. In terms of energy recovery the facility is perhaps best viewed as a natural gas fired CCGT power plant

with the incinerator providing a secondary, relatively low carbon energy input (in the form of steam) to the heat recovery boiler. An overview of the process is shown in the cut-through diagram below.

Figure 2-8-2: Schematic process flow diagram of the Bilbao plant



Source: Martin GmbH

Waste reception, storage and feeding

Waste is delivered by trucks to the tipping hall, which is maintained under negative pressure. Two crane grabs mix and sort the waste which is fed to a feed hopper.

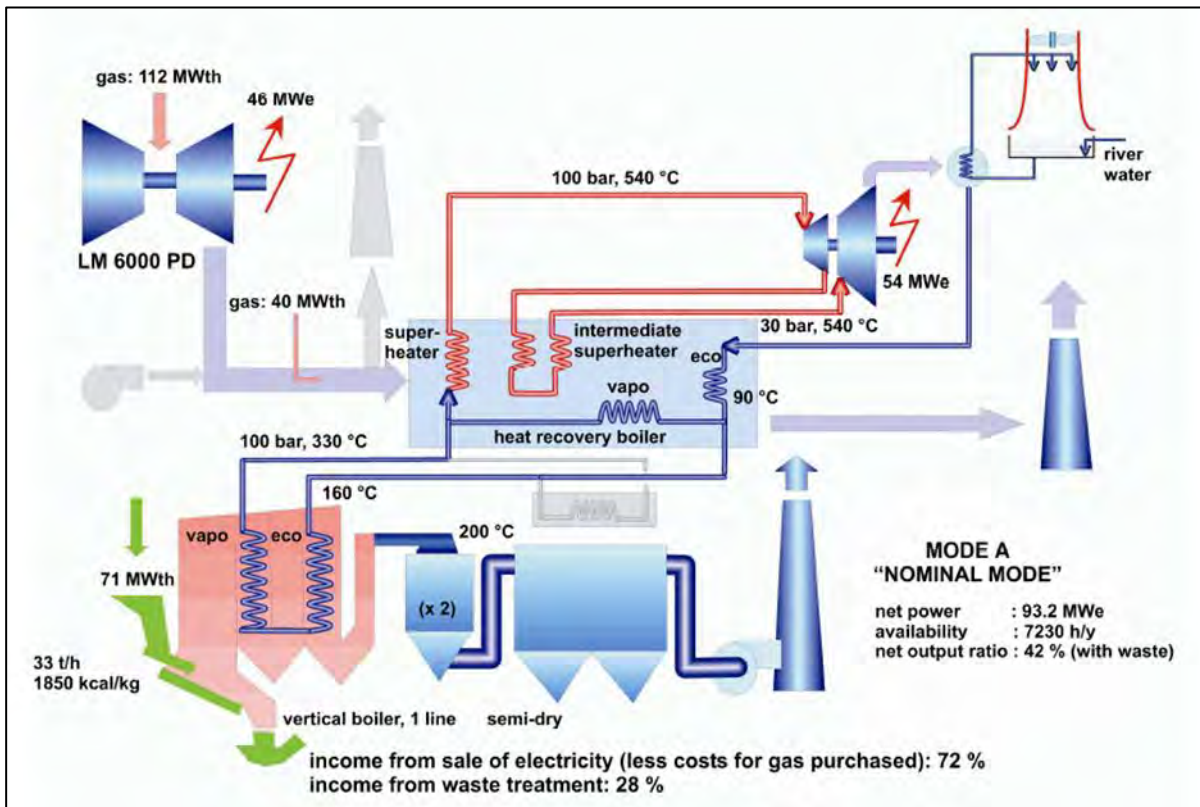
Combustion

The plant uses a conventional moving grate combustion system supplied by Martin GmbH. Waste is fed to a single 30 tonne per hour reverse-acting grate. The grate is air cooled, with primary combustion air fed under the grate and secondary air introduced higher up the furnace.

Energy Production

The plant uses a CCGT process to generate electricity from waste and natural gas at high efficiency, as shown in the diagram below.

Figure 2-8-3: Schematic diagram of the steam cycle at the Bilbao plant



Source: Martin GmbH

Heat from the flue gas is recovered in the boiler. Steam is produced at around 100bar, significantly higher pressure than in a conventional plant, though the temperature is limited to around 330°C in order to prevent excessive corrosion of the superheater tubes, which occurs as a result of the high chlorine content of MSW. The steam temperature is actually somewhat lower than that in most modern WtE plants (which typically produce steam at temperatures at or approaching 400°C), which helps minimise corrosion and hence operational costs and downtime. In a conventional WtE plant this superheated steam would be sent directly to a steam turbine, however at Zabalgarbi the steam passes to a second heat recovery boiler.

Independent of the WtE process, a 46MW gas turbine produces electricity from natural gas. The hot exhaust gases from this turbine contain substantial energy and are passed to the heat recovery boiler. The hot exhaust gases raise the temperature of the 100 bar steam from the WtE process from 330°C to 540°C (at constant pressure). Corrosion is not an issue in this boiler as the exhaust gases from the gas turbine are free of impurities capable of corroding the boiler tubes.

The superheated steam is then passed to a two-stage, 56MW steam turbine which uses a reheat cycle to further increase efficiency. Steam is expanded through the first high-pressure stage, dropping the pressure to 30 bar. It is then passed back through the heat recovery boiler where it is reheated to 540°C, and passed through the low-pressure stage. Exhaust steam is then condensed in a water cooled condenser which uses water from the nearby Kadagua River. Water cooled condensers are more effective than air cooled condensers at cooling and condensing the steam exiting the turbine, which gives a further slight increase in efficiency over a conventional plant. An on-site water treatment plant cleans the river water to a standard suitable to use at the plant.

Air Pollution Control

The Zabalgardi plant has a conventional air pollution control system to treat the flue gases from the waste combustion process:

- Control of combustion (850°C, 2 seconds);
- Reduction of NO_x (ammonia injection and flue gas recirculation);
- Acid Gases (SO₂, HF, HCl) semi-dry system, spray drier with lime injection;
- Elimination of heavy metals, dioxins/furans, and other pollutants by adsorption via active carbon injection;
- Bag filter – for dust removal;
- Monitoring and control of parameters for emissions into the atmosphere.

A selective non-catalytic reduction (SNCR) system is the primary method of reducing NO_x; in this process ammonia is injected into the high temperature flue gases in the boiler (around 850°C) which reacts with a proportion of the NO_x to form N₂ and H₂O. Additionally a proportion of the cleaned flue gases are recirculated to the boiler with the combustion air, with the combined benefit of increasing boiler efficiency (as a result of a reduction in excess air) and reducing the formation of thermal NO_x. Flue gases exiting the boiler then pass through a wet scrubber with lime injection to remove acid gases. Activated carbon is injected into the gas stream to remove remaining heavy metals, dioxins and furans, with a bag filter used to remove remaining particulates and residues from the APC process. The cleaned flue gases exit the plant via the stack.

Flue gases from the gas turbine are rejected via a separate, lower stack. The exhaust gases do not require cleaning as the controlled combustion of natural gas in a turbine releases minimal hazardous or harmful substances given the high purity of the fuel.

Ash Handling and Processing

Bottom ash from the process is used in the construction industry as an aggregate. Recovered metals are recycled. Fly ash is recovered and stabilised via an inertisation process to prevent leaching of heavy metals, and sent to storage in an authorised facility.

Plant Performance

MSW Processed

The plant is capable of processing between 230,000 and 250,000 tonnes per year of MSW from Bilbao. However, the availability in 'normal' operation mode of 7,320 hours per year (83.5%) implies a total of around 220,000 tonnes per year used in the combined cycle process (maximum energy recovery) in practice. The plant is capable of incinerating waste without utilising the combined cycle, but there will be no energy recovery under such circumstances (and hence substantially reduced revenues).

Based on the 'normal' availability, the waste input to the plant has an energy content of approximately 520 GWh per year. The plant also consumes approximately 820 GWh of natural gas per year.

Power and Heat Generation

The rated gross output of the plant is 99.5MWe. The net output is 95MWe. The quoted efficiency of the plant varies somewhat according to differing sources, but the net electrical efficiency appears to be around 42%.

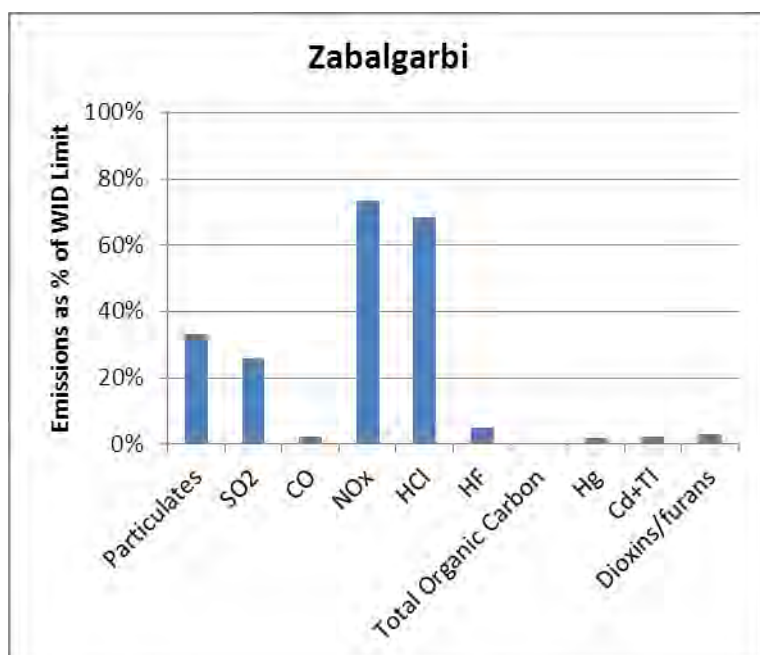
Typical modern WtE plants are limited to a gross electrical efficiency of around 25%. Zabalgardi S.A. suggest this is equivalent to an additional 10.5MWe above what a 'standard' WtE plant of the same capacity would typically achieve, close to double the overall efficiency. However, they assume a figure of 12MWe for a 'standard' plant which is very low; a net output of at least 15MWe could be expected for a modern plant (based on 20% net efficiency). Regardless, the Zabalgardi plant clearly represents a substantial increase in efficiency over what is possible using a conventional steam cycle.

Environmental Performance

Emissions to Air

The Zabalgardi plant performs well within WID limits for air emissions. Average emissions from the plant in 2008 are provided in the figure below.

Figure 2-8-4: Emission data from the Bilbao plant for 2008



Source: WSP analysis of plant data

Three air quality monitoring stations have been set up at Arraiz (Bilbao), Alonsotegi and Larrazabal. Particulates (PM₁₀), O₃, NO_x, SO₂, CO and HCl are continuously monitored at these stations.

Emissions to Water

No data regarding emissions to water is available, but it is understood that surface water sampling is carried out.

Emissions to Land

There are no emissions to land under normal operation. Bottom ash and metals are recycled and fly ash is sent to a secure storage facility.

Footprint and Visual Impact

The plant footprint covers 2.7 hectares, in a total site area of just over 5 hectares which includes gardens and roadways. The plant is remote from the main populated areas, but its location on a hillside above the city is relatively prominent.

The water cooled condenser often produces a visible plume, which is not an issue for the majority of WtE plants, which typically use air cooled condensers. However, the water cooled condenser is more effective and more compact; an equivalent capacity air cooled condenser would need to be very large and would increase the overall footprint of the facility.

Figure 2-8-5: The Zabalgarbi waste to energy facility



Source: Bizkaia Waste to Energy Plant, Summary Report, Feb 2005

Operability, Reliability and Availability

The original steam turbine was found to be defective in 2005, and the plant was shut down for three months in 2006 while it was replaced

The plant has been designed for flexibility and has seven modes of operation:

- Mode A: Normal Operation;
- Mode B: Combined Cycle Operation;

- Mode C: Fresh air mode;
- Mode D: Incineration and gas turbine through bypass stack;
- Mode E: Gas turbine through bypass stack;
- Mode F: Incineration only;
- Mode G: Shutdown.

Economics

It is understood that the total investment in the plant was €154M²².

Zabalgardi chose to build the project using a 'Project Finance' model, with a high debt to investment ratio, financing and debt payment agreed prior to construction and no parent company guarantees. The lack of parent company guarantees required firm contracts to be drawn up between all parties. A total of €55M was raised to start the project via shareholders, with an additional €2.4M provided by the European Union Thermie programme.

The ownership structure of Zabalgardi S.A is as follows:

Private: 65%

- SENER: 30%
- VTR (FCC): 30%
- BBK: 5%

Public: 35%

- Diputación Foral de Bizkaia: 20%
- Ente Vasco de la Energía: 10%
- Mancomunidad de Municipios de la Margen Izquierda: 5%

The Bilbao combustion facility is an example of a modern plant utilising the exhaust heat from an adjacent gas turbine power plant to perform reheating of the steam produced by the heat recovery boiler and operate with a thermal efficiency >40%.

²² <http://www.gara.net/paperezkoa/20080304/65668/es/Zabalgardi-alcanza-su-capacidad-maxima-abrira-otra-linea-para-2012>.

Case Study 9 – Brescia, Italy

Overview

The ASM Brescia 'Termoutilizzatore' (waste-to-energy plant) plant was built in 1998 and is one of the main providers of district heating in the city of Brescia. It is situated in the southern suburbs of the city, in an area of approximately 160,000 m²; the surrounding area is characterised by mixed settlements of industrial and residential properties. To the north is the Lamarmora thermal power station, warehouses, factories, and offices.

Figure 2-9-1: Photographs of the plant



Source: Bonomo A, Waste to Energy Experiences – The Brescia Experience; WTERT Council, April 2003

The construction phase was a turnkey project delivered by the consortium of multi-fuel biomass boiler, solid fuel handling equipment and control system suppliers Ansaldo, Martin and ABB. It operates three lines, two for the combustion of household waste operating since 1998 and a third for biomass operating since 2004. The biomass has thermal capacity of about 100MW and is amongst the world's largest combustion lines for biomass.

In 2011 the plant processed 796,000 tons of waste and biomass, producing 602 million kilowatt hours of electricity and 747 million kilowatt hours of heat i.e. almost 55% of the thermal energy fed into the Brescia grid. In the same year the plant produced electricity equal to the needs of about 200,000 households and heat equal to the needs of more than 60,000 apartments. At the same time it achieved savings of more than 150,000 TEP (tonnes of oil equivalent) and avoided the emission of 400,000 tons of carbon dioxide.

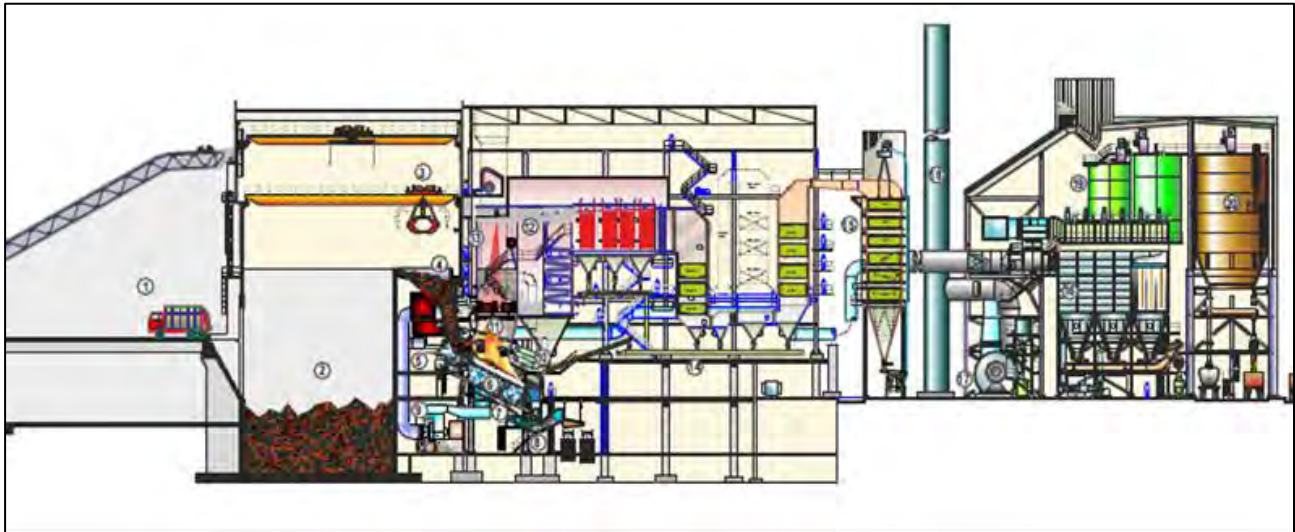
To ensure transparency for information on the operations of the plant, the City Council of Brescia established a "Waste Incinerator Observatory", for monitoring and communicating its activities. Observatory Reports are available on the website of the Municipality of Brescia²³.

The plant design yields an electrical net efficiency of greater than 27%, with the actual figure depending on the lower heating value of waste and degree of cogeneration.

²³ <http://www.comune.brescia.it/Istituzionale/AreeESettori/AreaGestioneDelTerritorio/AmbienteEdEcologia/termoutilizzatore.htm>

The Process

Figure 2-9-2: Schematic of the process



| | | | |
|----------------|---------------------------------------|-------------------------|------------------|
| 1 Tipping Hall | 6 Martin Reverse-acting Grate | 11 Furnace | 16 Fabric Filter |
| 2 Bunker | 7 Grate Sittings Conveyer | 12 Steam Boiler | 17 ID Fan |
| 3 Waste Crane | 8 Martin Discharger | 13 Nox Reduction (SNCR) | 18 Stack |
| 4 Feed Hopper | 9 Underfire air system with preheater | 14 Fly Ash Transport | 19 Additive Silo |
| 5 Feeder | 10 Over fire air system | 15 External Economiser | 20 Residue Silo |

Source: Martin GmbH

The key features are approximated as follows:

- Throughput of waste 800,000 tonnes per annum;
- Produces 150,000 tonnes of bottom ash per annum;
- Estimate 20,000 tonnes Air Pollution Control residues per annum;
- Steam pressure 72 bar;
- Steam temperature 450⁰C;
- Electricity generation 100MW_e;
- Production of 570 MWh of electricity (2008), and
- Production of 568 MWh of heat (2008).

Waste reception, storage and feeding

The waste reception hall operates under on a closed negative pressure system to avoid odour emissions. The plant has storage capacity in excess of 30,000 m³.

Figure 2-9-3: The waste bunker



Source: Bonomo A, Waste to Energy Experiences – The Brescia Experience; WTERT Council, April 2003

The waste is discharged from refuse vehicles into the tipping hall and then thoroughly mixed in the bunker by a crane prior to being fed into one of the feed hoppers of the three process trains.

Figure 2-9-4: The crane operators



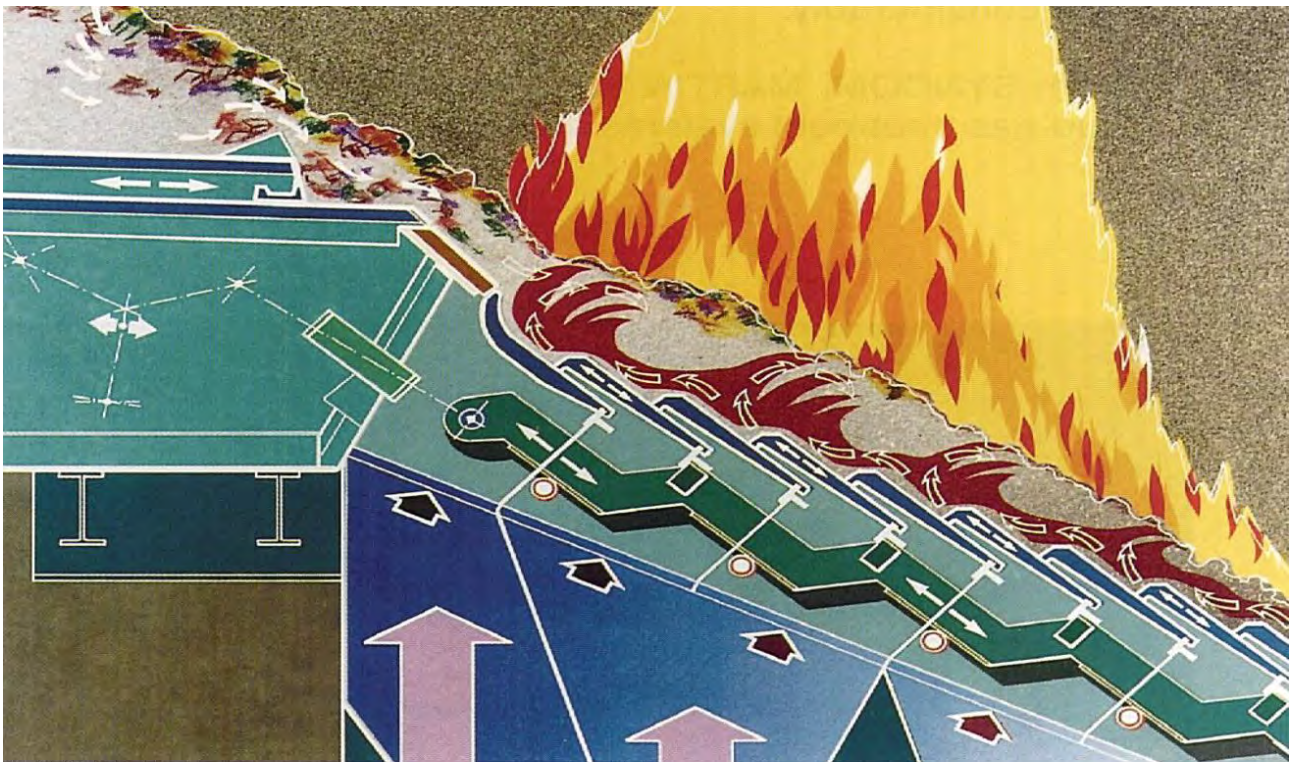
Source: Bonomo A, Waste to Energy Experiences – The Brescia Experience; WTERT Council, April 2003

Combustion

The feeder moves the waste to the moving reverse thrust grates, each consisting of 6 parallel lanes that have 15 steps in motion to allow effective mixing of the waste and facilitate combustion. The area below is divided into 30 sections through which air is introduced. At a height of about 3 m above the grid, secondary air and flue gas recirculation (taken downstream of the purification system) are injected from the front and back walls, to support complete combustion.

The temperature of combustion is automatically adjusted to about 1,100°C to eliminate organic pollutants present in the waste and at the same time, reduce the formation of Oxides of Nitrogen and Carbon Monoxide. At the afterburner stage a mixture of water and ammonia is injected and vaporised to reduce nitrogen oxides levels. The hot flue gases then enter the boiler for the steam generation stage and the slag collects at the bottom of the grid.

Figure 2-9-5: Schematic of the Martin grate



Source: Martin GmbH

Energy Production

Inside the boiler the hot exhaust gases from the combustor is passed through the heat exchanger where the pressurised water is heated, and the evaporator, vapour bubbles and becomes saturated is finally superheated. The water enters the boiler, at a pressure of 80 bar and at a temperature around 130°C. The steam leaves the boiler at a pressure of 72 bar and at a temperature of about 450°C.

Air Pollution Control

The plant is designed to meet the requirements of the Waste Incineration Directive (WID) as a minimum for emissions release. The facility utilises dry lime injection, carbon injection and a bag house for emissions control, with an ammonia based SNCR NO_x removal system. The plant has also trialled a high dust SCR catalyst system.

The hydrated lime combines with the harmful substances that are found in the gaseous state, in particular hydrochloric acid, hydrofluoric acid, sulphur dioxide and trioxide, forming calcium salts which precipitate in the solid phase as dust held from the filter. The activated carbon adsorbs residual micro-pollutants (including heavy metals, dioxins and furans) by incorporating them in the dust. The filter "sleeves" are made of special synthetic fibres and each is seven meters long with a diameter of 13 centimetres. Each line has a filter system composed of approximately 2000 sleeves.

The layer of powder that is formed on the outside of the sleeves is periodically "Shaken" mechanically by means of pulses of compressed air. The dust retained by the filter is collected in hoppers located on the bottom of the filter and then periodically conveyed to storage silos.

Ash Handling and Processing

Each line has its own hermetically sealed system for the removal of residues and the removal of dust from the boiler and filters. Bottom ash has two removal points for each boiler, two lines of vibrating conveyors and each line is equipped with magnetic iron recovery.

Combustion slags (equal to about 20% of mass of the waste treated), are used in a number of applications e.g. authorised landfills as substitution for daily covering of waste and for internal roads and a variety of construction uses.

APC residues from the gas cleaning is treated to deactivate the ash i.e. reduce the leaching potential of key pollutants, and is then taken for deep mine storage in Germany.

Plant Performance

MSW Processed

Total waste throughput is in the region of 800,000 tonnes per annum. The main fuels are municipal solid waste, industrial (non-hazardous) waste, biomass (biodegradable waste, food preparation, wood processing residues, paper and board packaging and demolition wood) and dried sludge from sewage treatment plants. In 2011 the biomass content of waste processed was in the region of 40%. A more detailed breakdown of waste type and quantities received each year is available in the annual environmental report.

The plant was designed for a wide range of waste compositions with LHV in the range 6,300-13,800 kJ/kg.

Brescia has a separate collection system for recycling waste, bio-waste and residual solid waste. The recycling rate in Brescia is around 40%.

Support and start-up fuel is natural gas.

Power and Heat Generation

The process steam generated by the three combustion lines drive a thermal cycle turbine generator, capable of generating both heat and electric power or heat only or electricity only. The link-up with the existing Lamarmora plant makes it possible to operate the district heating section “in series” with the heat exchangers of the existing turbo-generators. This optimises the global efficiency of the entire plant. To maximise power generated and heat recovered using the district heating network, the plant is designed to operate at full capacity during the working days and at minimum capacity during the night and weekends.

Environmental Performance

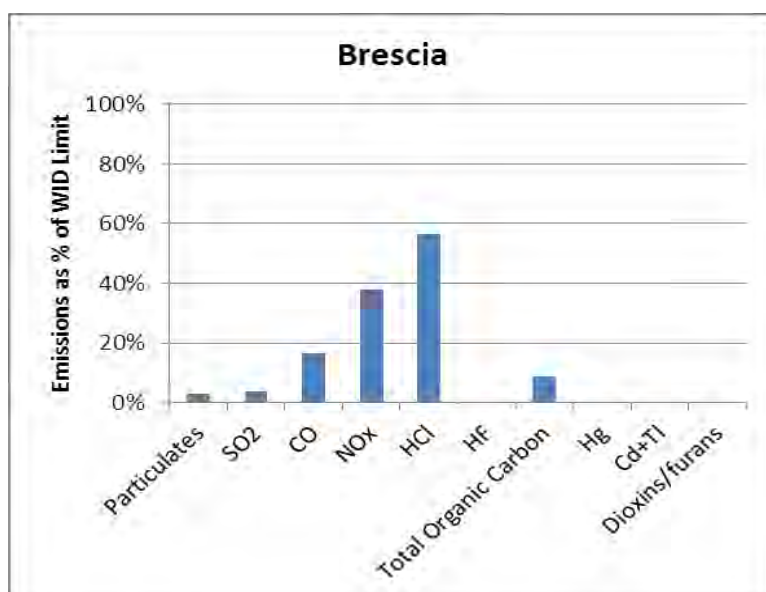
Emissions to Air

Emissions to the atmosphere from the plant are monitored continuously, periodically controlled by ARPA, for the analysis of the following parameters:

- Oxygen (O_2)
- Carbon monoxide (CO)
- Sulphur dioxide (SO_2)
- Oxides of Nitrogen (NO_x)
- Hydrochloric acid (HCl)
- Particulates
- Total organic carbon (TOC)
- Ammonia (NH_3)

Dioxin monitoring is undertaken on a campaign basis, not continuously as above (shown as the sum of all dioxins expressed as toxic equivalency).

Figure 2-9-6: Average 2011 monthly concentration levels for pollutants



Source: WSP analysis of plant data

Data for HF, Hg, Cd and dioxins/furans was missing.

Weekly air emission reports can found at the following address:

http://www.a2a.eu/gruppo/cms/a2a/it/sostenibilita/emissioni/emissioni_interna.html?codiceImpianto=BS01

Emissions to Water

The plant has been designed for minimum water usage and there is no industrial water effluent from the plant. The process of Cogeneration means the need for heat dissipation is limited, compared to a conventional thermoelectric power plant, because the heat produced by the condensation of steam released from the turbine is largely injected into the district heating network.

Emissions to Land

Incinerator Bottom Ash (IBA) is produced at approximately 150,000 tonnes per annum, including metals. The metals are removed magnetically and sent for recycling mainly in foundry applications.

The residual IBA free of loose metal is ate (IBAA) and is used in building and civil engineering applications or reused in authorised landfill applications.

The APC residues are classified as hazardous waste and are pre-treated prior to collection for deep mine disposal in Germany.

Footprint and Visual Impact

The total area of the facility is 160,000 m² of which 23,724 m² is the buildings.

The architectural design of the plant and its integration into the landscape was been a key objective from the outset. The basic idea was to achieve a harmonious placement in the environment; even the stack is painted in a graduated sky blue aimed at reducing the visual impact.

Figure 2-9-8: The Brescia waste to energy plant



Source: Bonomo A, Waste to Energy Experiences – The Brescia Experience; WTER Council, April 2003

ASM Brescia facility won the WTER 2006 Industry Award for demonstrating the best combination of electrical and thermal energy recovery, low emissions and aesthetic appearance.

Operability, Reliability and Availability

The plant uses a high level of monitoring and automated systems (15,000 parameters are measured and transmitted up to the main control room). There is a distributed control system (DCS) and the lower hierarchic levels can operate in the event of failure of the upper levels. There are in the region of 50 cameras in the plant monitored in control room.

For recent years, the production of electricity in 2009 was lower than in previous years due to work undertaken on the turbine alternator between February and April. In 2010, the production of electricity and heat increased as a result of upgrading work on lines 1 and 2 and the repowering of the turbine.

Economics

The estimated capital cost for the plant £320M.

The Brescia WtE facility is a true state-of-the-art plant with low emissions and high efficiency power production. The architectural look of the plant is also extremely modern.

Case Study 10 – Riverside, London, UK

Overview

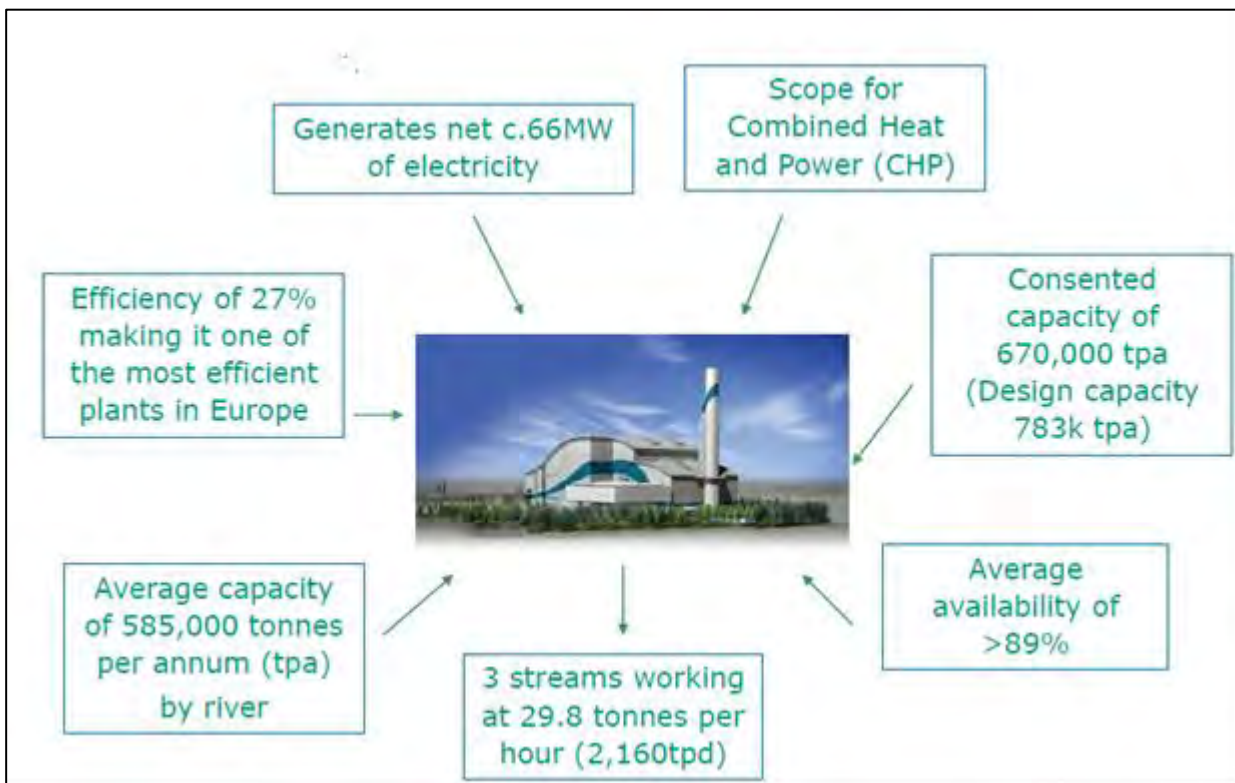
The Riverside energy-from-waste plant at Belvedere is an important strategic river-served waste management facility for London, keeping over 100,000 HGVs off the capital's roads each year and producing electricity for more than 66,000 homes, potentially up to 100,000. The facility is owned and operated by Riverside Resource Recovery Ltd, a subsidiary of Cory Environmental. The energy recovery concept of the facility is also designed for potential off-take of steam or hot water for district heating purposes for future developments.

The key outputs are approximated as follows:

- 66MW electricity generation;
- Potential for generating 478,000 MWh per annum;
- 150,000 tonnes of bottom ash, and
- 23,000 tonnes Air Pollution Control residues.

Over 80% of waste processed is delivered by river barge, estimated at 536,000 tonnes, with London Borough of Bexley delivering the remaining 80,000 tonnes by road.

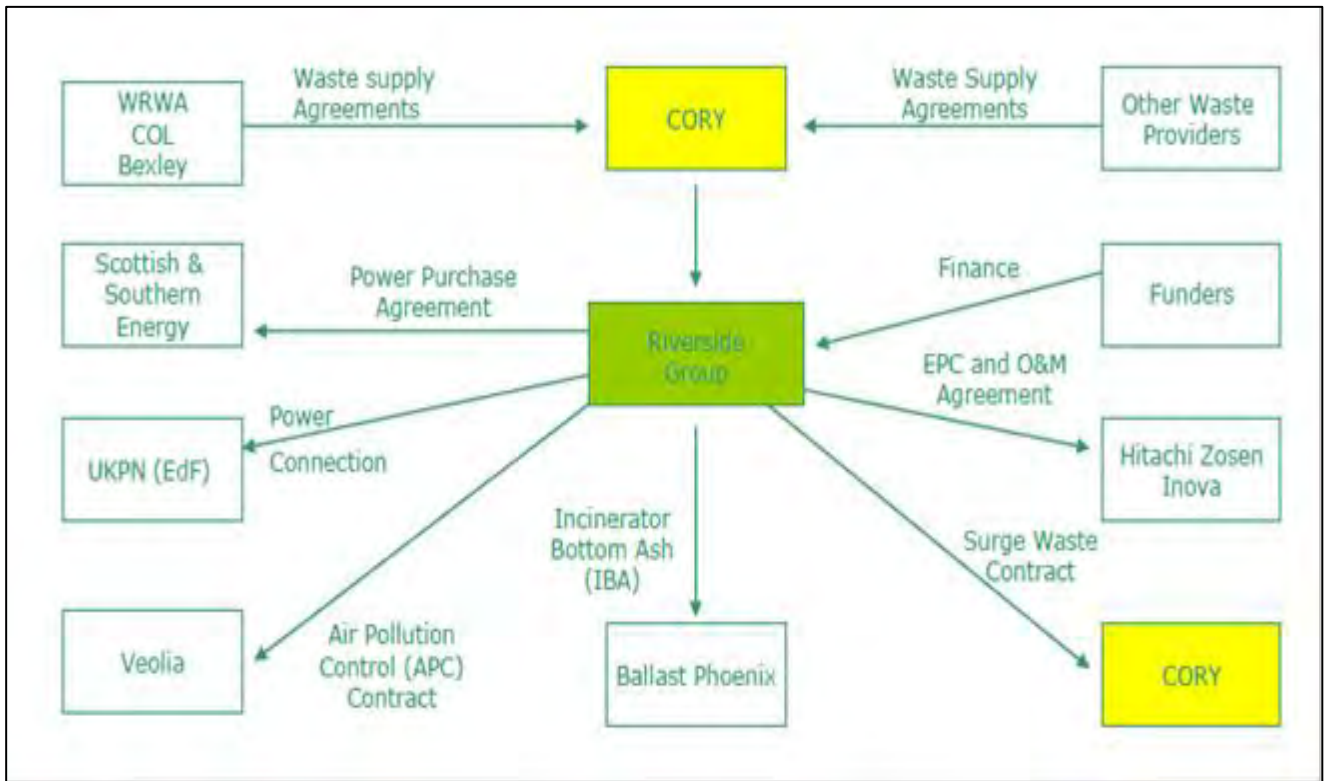
Figure 2-10-1: Technical details of the Riverside waste to energy plant



Source: CIWM Waste Seminar, Martyn Hunt presentation, June 2011

Contracting Structure

Figure 2-10-2: Details of the contract structure for the Riverside project



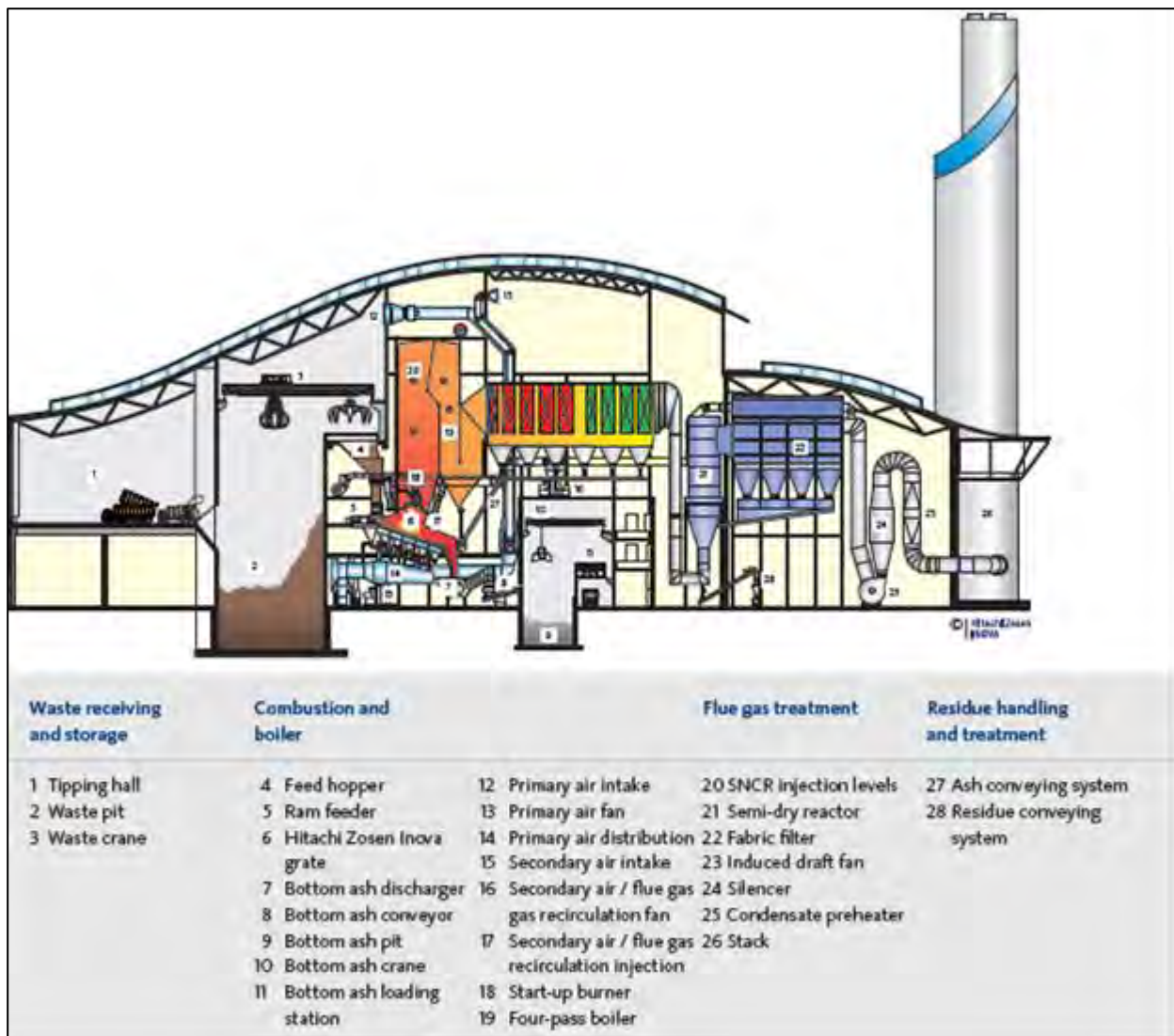
Source: CIWM Waste Seminar, Martyn Hunt presentation, June 2011

The Process

The key features are approximated as follows:

- Maximum through put waste: 670,000 tonnes per annum;
- Waste throughput per stream: 31.8 tonnes per hour;
- Steam produced per stream: 54 tonnes per hour;
- Steam pressure: 72 bar;
- Steam temperature: 427°C;
- Flue gas outlet temperature: 190°C;
- Electricity generation: 66MW.

Figure 2-10-3: Schematic representation of the process flow for the Riverside plant



Source: Hitachi Zosen Inova

Waste reception, storage and feeding

Figure 2-10-4: Waste delivery jetty arrangements at the Riverside waste to energy plant



Source: CIWM Waste Seminar, Quentin Gillett presentation, June 2011

Approximately 15% of the waste is delivered to the site directly by road; the remaining 85% of the waste is delivered to the site by barges. At the jetty, the containers are unloaded onto vehicles, which then off-load the residual waste into a bunker within the waste reception hall.

Figure 2-10-5: Waste unloading at Riverside



Source: CIWM Waste Seminar, Quentin Gillett presentation, June 2011

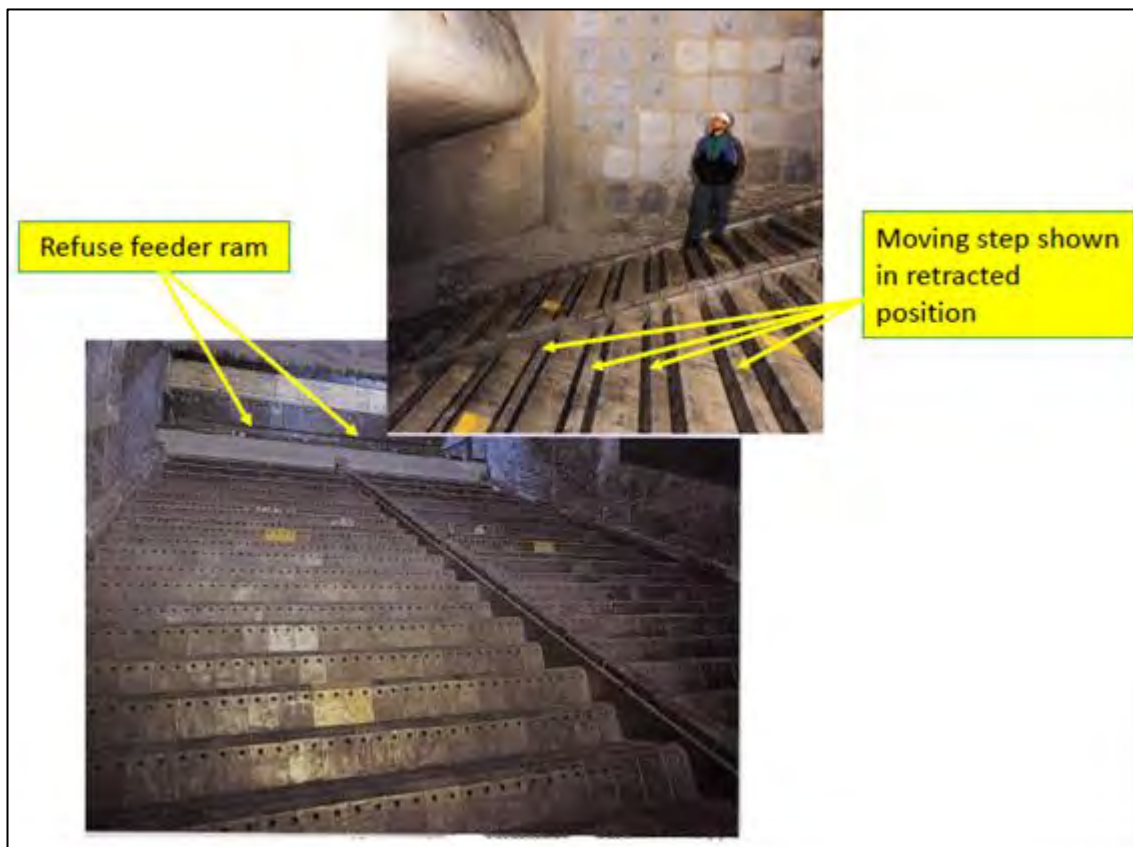
The waste is then thoroughly mixed in the bunker by a crane and then fed into one of the feed hoppers of the three process trains. Each train has a four-pass boiler with a thermal capacity of 79.5 MW. The waste passes down a feed chute onto the four-row grate.

Combustion

The moving grate mixes and agitates the waste to allow an optimal burnout of the diverse waste fractions. In addition to this, a fully integrated control system allows for continuous adjustments of combustion conditions for the safest and most efficient operation possible. The process reduces the waste volume received by up to 90%. The burnt out ash passes through the ash discharger onto an ash handling system.

Pyrolytic gas produced in the combustion process pass is mixed with secondary air and recirculated flue gas, which are injected tangentially at high velocity into the secondary combustion chamber above the grate, resulting in intensive mixing and the complete burnout of the pyrolytic gas. This is a first step in reducing emission levels. In parallel, the NO_x-levels are maintained by means of Selective Non-Catalytic Reduction.

Figure 2-10-6: The Hitachi Zosen Inova grate used in the Riverside plant



Source: CIWM Waste Seminar, Quentin Gillett presentation, June 2011

Energy Production

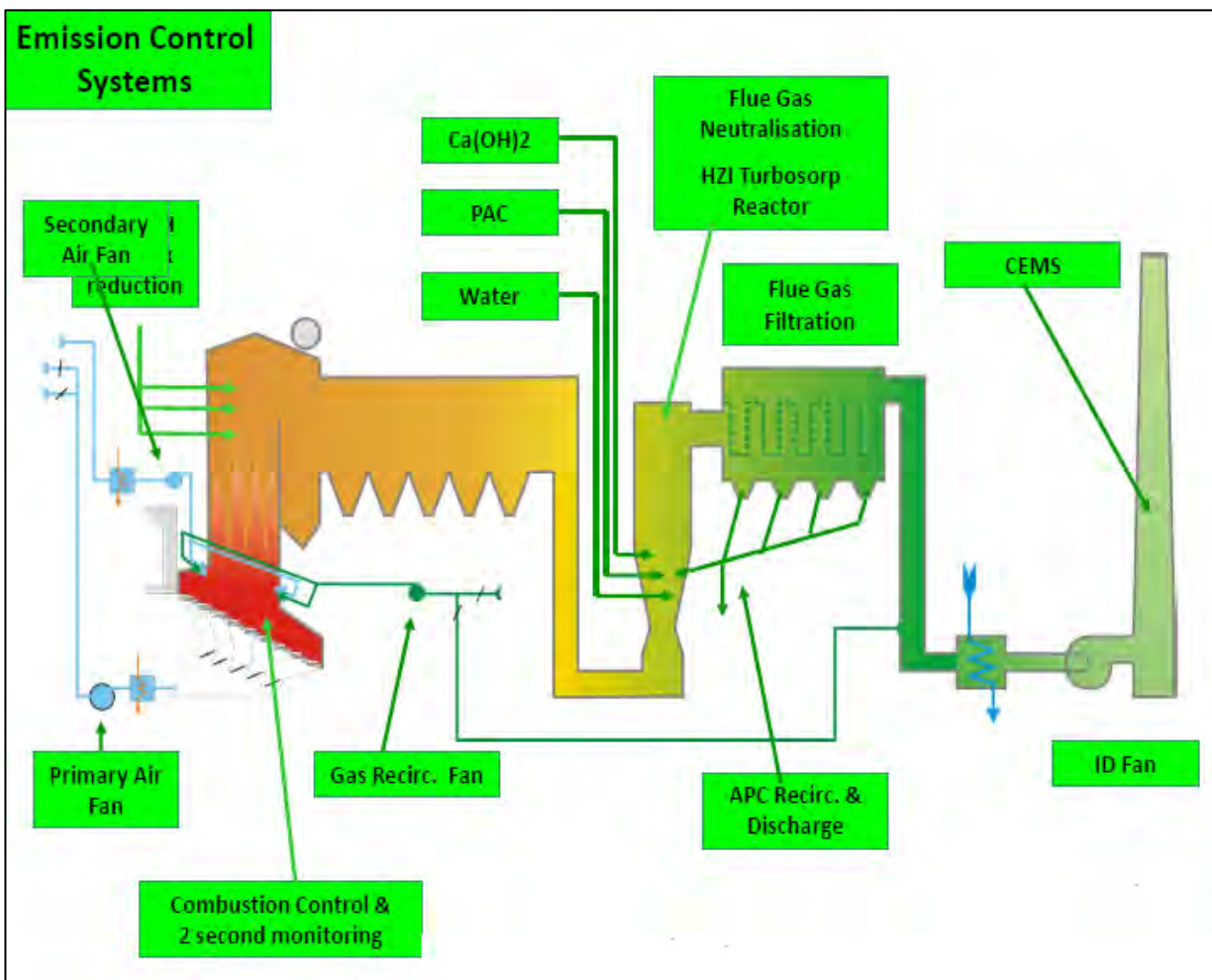
The raw gas passes through a water tube boiler where it is cooled while the water of the closed water-steam cycle is superheated. The superheated steam is then expanded by means of a turbo-generator. The electricity produced is in part used to supply the facility with the remaining 90% plus exported to the national grid.

The energy recovery concept of the facility is also designed for potential off-take of steam or hot water for district heating purposes for future developments.

Air Pollution Control

The plant is designed to meet the requirements of the Waste Incineration Directive (WID) as a minimum for emissions release.

Figure 2-10-7: Schematic diagram of the gas cleaning processes used at Riverside



Source: CIWM Waste Seminar, Quentin Gillett presentation, June 2011

Cleaning takes place in a semi-dry system consisting of a reactor in combination with a fabric filter. Flue gases leave the boiler and enter the Turbosorp reactor tower where lime, activated carbon and water are added for the removal of gaseous pollutants, including heavy metals and dioxins, and small particles are separated in the three fabric filters. The clean hot gas is drawn from the bag filters and through a heat exchanger allowing heat to be transferred from the gas to the boiler feed water. The APC residues are retained on the bag wall where compressed air shakes them off into silos ready for collection by road tanker; they are sent for safe treatment and disposal by Veolia Environmental Services at an appropriate facility. An induced draught fan from each of the three lines draws the clean cooled gas up the 85m stack where it is finally released into the atmosphere.

Ash Handling and Processing

Two types of solid residues are generated by the combustion process; incinerator bottom ash (IBA) and air pollution control (APC) residues from the abatement equipment.

Figure 2-10-8: Bottom ash grab and loading hopper



Source: CIWM Waste Seminar, Quentin Gillett presentation, June 2011

The Incinerator Bottom Ash (IBA) is produced at approximately 150,000 tonnes per annum, including metals. It is transported ten miles along the river by barge to a new processing facility at Tilbury docks where the ash is prepared for use as an aggregate for road building and construction.

The management of APC residues, 22,000 tonnes, is contracted to Veolia Environmental Services who pre-treat the residues prior to secure landfill.

Plant Performance

MSW Processed

The feedstock to the plant consists of municipal solid waste with permitted processing capacity of 670,000 tonnes per year (design capacity 783,000). The plant was designed with the capability for burning materials with an average Net Calorific Value (NCV) between 7.0 MJ/kg and 13.0 MJ/kg.

Power and Heat Generation

The facility generates 66MW of electricity annually the vast majority of which is exported to the National Grid, enough to meet the domestic needs of approximately 66,000 homes. Riverside also has the potential to supply surplus heat to local infrastructure, giving it the potential to operate as a Combined Heat and Power (CHP) plant in future.

Environmental Performance

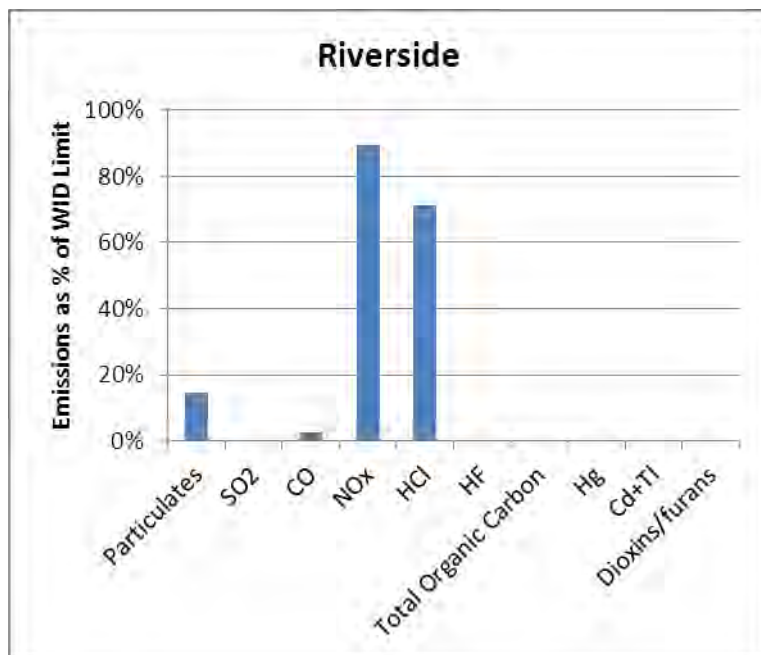
Emissions to Air

Monthly air emission reports can found at the following address:

<http://www.coryenvironmental.co.uk/page/rrremissions2012.htm>

The format used to report emissions is as follows:

Figure 2-10-9: Emissions data for August to October 2012



Source: WSP analysis of plant data

Emissions to Water

The plant has consent to discharge any process waste water to foul sewer to an authorised specification issued by Thames Water prior to commencing operations. A periodic sampling and monitoring regime has been established to comply with the requirements of operational permits.

Emissions to Land

Incinerator Bottom Ash (IBA) is produced at approximately 150,000 tonnes per annum, including metals. It is transported ten miles down the river by barge to a new processing facility at Tilbury docks where the ash is prepared for use as an aggregate for road building and construction.

When the IBA arrives at the processing facility it is stored in the open for a few weeks to weather before being processed through the plant. The IBA is separated into various size fractions with any remaining metals extracted and sent for further processing. The subsequent processing stages include washing, screening, crushing and scrubbing. The finished product is now classified as incinerator Bottom Ash Aggregate (IBAA) and is ready to be used in building and civil engineering applications.

IBAA from Cory's Riverside Resource Recovery Energy-from-Waste facility has been used on the major M25 widening scheme. Other applications for processed IBA include fill material, asphalt and foamed asphalt, cement bound materials, lightweight blocks, foamed concrete and pavement concrete.

The facility at Tilbury Docks is operated by Ballast Phoenix and was purpose-built to handle up to 170,000 tonnes per year ash, predominantly from Belvedere. The plant was part-funded by Cory Environmental and was completed in May 2011 at a cost of £5m. It is regulated by the Environment Agency.

Figure 2-10-10: Aerial image of the Riverside Resource Recovery's Crane at berth 22 and the Ballast Phoenix IBA processing site, berth's 36/38.



Source: CIWM Waste Seminar, Martyn Hunt presentation, June 2011

Figure 2-10-11: IBA produced by the Riverside plant, raw bottom ash (left), with metals removed (right)



Source: CIWM Waste Seminar, Martyn Hunt presentation, 24 June 2011

The APC residues are classified as hazardous waste and are taken to a Veolia Environmental permitted treatment facility where they are conditioned and treated, prior to landfill. The landfill regulatory controls applied in the UK are designed to prevent pollution of the environment due to leaching of polluting substances from waste such as APC residues.

Footprint and Visual Impact

Figure 2-10-12: A view of the Riverside Waste to Energy plant



Source: Hitachi Zosen Inova

Operability, Reliability and Availability

WSP understands that since the plant was commissioned and handed over to the client it has operated satisfactorily. The guarantee provided by Hitachi Zosen Inova (formerly Von Roll Inova) was for 8,000 hours per year of operation. WSP has requested actual data from the operators but they declined stating commercial confidence. WSP has no reason to doubt the plant is meeting its performance targets in relation to reliability and availability and we have seen no evidence within the technical media that this is not the case.

Economics

The estimated capital cost for the plant £320M.

No operating cost data was available.

The Riverside WtE plants has been 18 years in development, facing significant opposition and having to be subjected to two Judicial review processes before it was finally constructed.

The plant is an example of a modern state-of-the-art facility design and constructed by one of the leading companies – Hitachi Zosen Inova (formerly Von Roll Inova).

The majority of the waste is delivered to the plant in barges via the River Thames. The plant operates with increased steam conditions – 72bar and 427°C and the boiler has been designed specifically to produce steam at these conditions without the significant boiler fouling and failure that would have been experienced in the past. The plant operates with a relatively high thermal efficiency of 27%.

Case Study 11 – Mainz, Germany

Overview

The Energy from Waste facility at Mainz in Germany (the Entsorgungsgesellschaft Mainz mbH) and is owned by Entsorgungsges Mainz mbH and has been operational since 2003. The facility accepts waste from city of Mainz and neighbouring communities and also private waste disposal companies.

The facility was initially constructed with two process lines and a third was added in 2008 increasing capacity from a maximum of 230,000 tonnes per annum to 340,000 tonnes per annum. All three process lines are MARTIN Reverse-acting grates and were installed by Martin GmBH.

Attributes of the system are as follows:

- Three MARTIN reverse-acting grates
- Waste throughput:
 - Lines 1 and 2 - 16.2 tonnes/hr, CV - 9.8 MJ/kg
 - Line 3 – 17.8 tonnes/hr, CV - 9.7 MJ/kg
- Gross Heat Release:
 - Units 1 and 2 – 44 MW
 - Unit 3 – 48 MW
- Grate Width:
 - Units 1 and 2 – 5,945mm
 - Unit 3 – 6,320mm
- Steam Pressure – 42.3 bar
- Steam temperature:
 - Units 1 and 2 – 400°C
 - Unit 3 – 420°C
- The power generated in the plant is the equivalent to the electricity demand of 400,000 households
- The process exhaust gases are emitted to atmosphere via a 95m stack
- Exhaust gases omitted to atmosphere are subject to continuous and discontinuous measurement to ensure compliance with § 18 (public information) of the 17th BImSchV and are published on the facilities website (<http://www.mhkw-mainz.de/anlagentechnik/messwerte.php>). The half hourly and daily mean values are also transmitted to the competent licensing authority. The following is a summary of the emission limited in 17thBImSchV and the permitted limits for the facility:

Table 2-11-1: Permitted emission limits for the Mainz waste to energy plant

| Parameter Measurement) (Continuous | 17th BImSchV (mg/m³) | Actual Permitted Limits (mg/m³) |
|---|---|---|
| Carbon Monoxide (CO) | 50 | 50 |
| Total Dust | 10 | 8 |
| Total Carbon | 10 | 10 |
| Hydrochloric | 10 | 8 |
| Sulfur Dioxide (SO ₂) | 50 | 50 |
| Nitrogen Oxides (NO _x) | 200 | 150 |
| Mercury | 0.03 | 0.03 |
| Ammonia | - | 10 |

Source: <http://www.mhkw-mainz.de/anlagentechnik/messwerte.php>

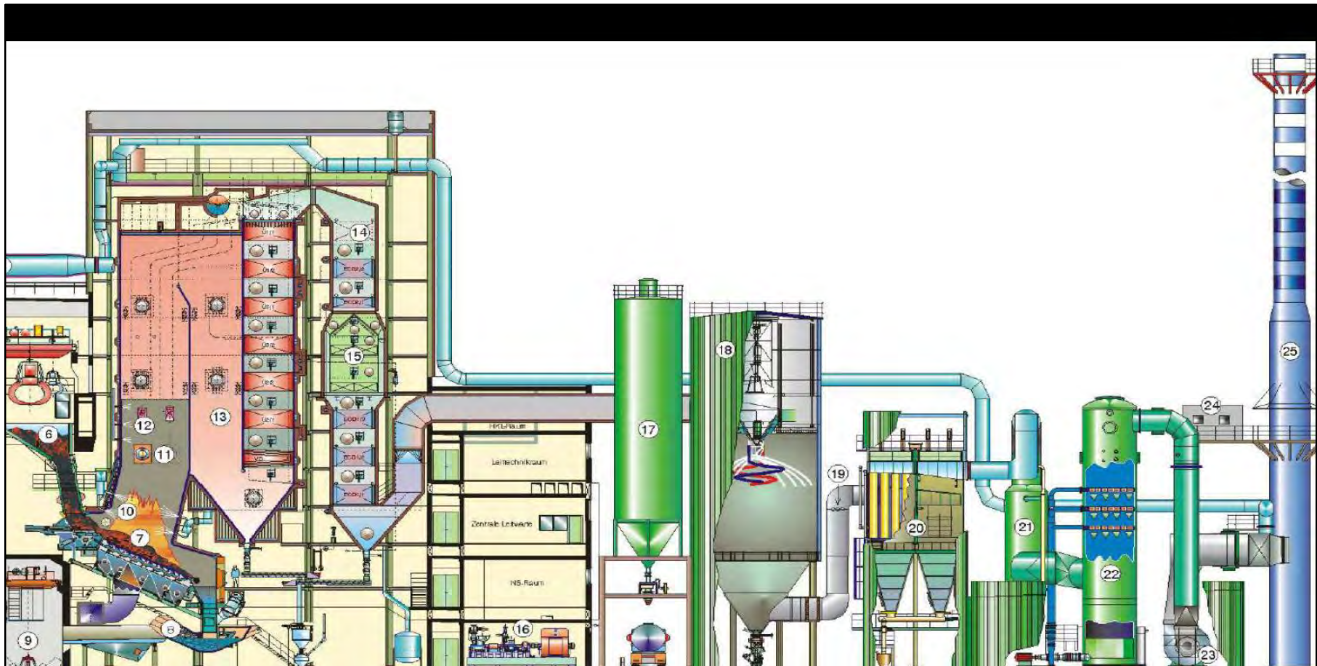
Table 2-11-2: Permitted emission limits for the Mainz waste to energy plant

| Parameter Measurement) (Individual | 17th BImSchV (mg/m³) | Actual Permitted Limits (mg/m³) |
|--|---|---|
| Cadmium and Thallium | 0.05 | 0.05 |
| Total Antimony, Arsenic, Lead, Chromium, Cobalt, Copper, Manganese, Nickel, Vanadium and Tin | 0.5 | 0.5 |
| Total Arsenic, Benzo Pyrene a, Cadmium, Chromium (VI) | 0.05 | 0.05 |
| Dioxins and Furans (ng/m ³) | 0.1 | 0.08 |

Source: <http://www.mhkw-mainz.de/anlagentechnik/messwerte.php>

The Process

Figure 2-11-1: Schematic process flow diagram

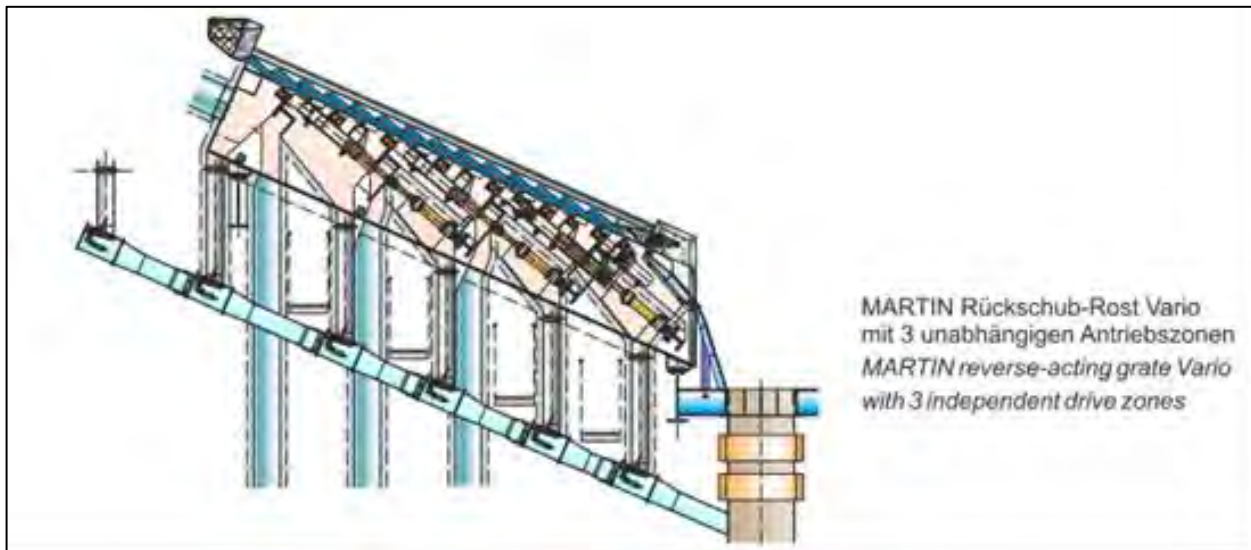


- | | |
|---------------------------------|--|
| 1. Unloading Hall | 14. Soot blower |
| 2. Shredder | 15. Slip catalyst converter |
| 3. Waste Bunker | 16. Turbine / generator for internal consumption |
| 4. Waste Crane | 17. Residue silo |
| 5. Under fire air intake | 18. Absorbers |
| 6. Feed hopper | 19. Absorbent injector |
| 7. MARTIN reverse-acting grate | 20. Fabric filter |
| 8. MARTIN discharger | 21. Pre-scrubber |
| 9. Bottom ash bunker | 22. Wet scrubber |
| 10. Over fire air system | 23. ID fan |
| 11. Ignition and support burner | 24. Measuring station |
| 12. NOx reduction (SNCR) | 25. Stack |
| 13. Steam boiler | |

Source: www.mhkn.mainz.de/EGM_infobro3_eng_20.pdf

The process lines are all MARTIN reverse-acting grates.

Figure 2-11-2: Diagram of the Martin reverse-acting grate



Source: MARTIN GmbH

http://www.martingmbh.de/index_en.php?level=2&CatID=8.47&inhalt_id=9&dCat=21&do=showDetail

The majority of the steam is fed to the neighboring 400 MW combined cycle power plant (CCPP) owned by Mainz-Wiesbaden AG where the steam is superheated to 550°C without using additional primary energy sources and is converted to electricity in a highly efficient manner using a gas turbine.

Waste reception, storage and feeding

Waste is transported to the facility by refuse collection vehicles and weighed electronically on a weighbridge. The waste consignment is then inspected to ensure that the waste complies with the declaration and is authorised for combustion in the Mainz plant.

Once the waste consignment is approved / accepted the vehicle proceeds to and unloads via one of seven tipping points into the sealed refuse pit. Bulky waste is shredded by rotary shears separately and transported to the refuse pit on a conveyor belt.

Source segregated biodegradable waste is deposited into compactors via disposal chutes and is recycled.

Two crane units are installed in the refuse pit and are used to load each combustion line to ensure efficient and constant combustion take place.

The required combustion air is extracted from the refuse pit by suction, which therefore generates negative pressure and prevents odours escaping into the tipping hall and into the ambient air.

Combustion

The Entsorgungsgesellschaft Mainz mbH facility utilises three MARTIN Reverse-acting grates of which lines 1 and 2 were commissioned in 2003 and line 3 was commissioned in 2008.

The initial capacity of the facility when constructed with lines 1 and 2 was 230,000 tonnes per annum, which was increased by approximately 50% to around 340,000 tonnes with the introduction of the third line.

Table 2-11-3: Technical data for the three combustion lines at the Mainz waste to energy plant

| Description | Lines 1 and 2 | Line 3 |
|-------------------------------|---------------------------------|---------------------------------|
| Commissioned | 2003 | 2008 |
| Waste Throughput (per unit) | 16.2 tonnes/hr, CV of 9.8 MJ/kg | 16.2 tonnes/hr, CV of 9.8 MJ/kg |
| Gross Heat Release (per unit) | 44MW | 48MW |
| Grate Width | 5,945mm | 6,320mm |
| Steam Pressure | 42.3 bar | 42.3 bar |
| Steam Temperature | 400°C | 420°C |

Source: Martin GmbH, presentation entitled Mainz, Germany {provided directly by Martin}

The residual waste that passes through the feed chutes of the three combustion lines is conveyed to the combustion grates by means of feed ram. Gas burners are used to start the combustion process which preheats the combustion chamber to the minimum required temperature of 850°C. Once the process has been initiated combustion takes place independently without any additional supply of primary energy. The gas burners are available for boosting temperatures during the operation of the facility, but are rarely used,

The air required for combusting the waste is extracted from the refuse pit, then preheated by heat exchangers and injected into the furnace. The combustion temperature exceeds 1,000°C.

The combustion residue remaining on the grate after a residence time of approximately one hour is transported to the bottom ash bunker via a wet-type discharge.

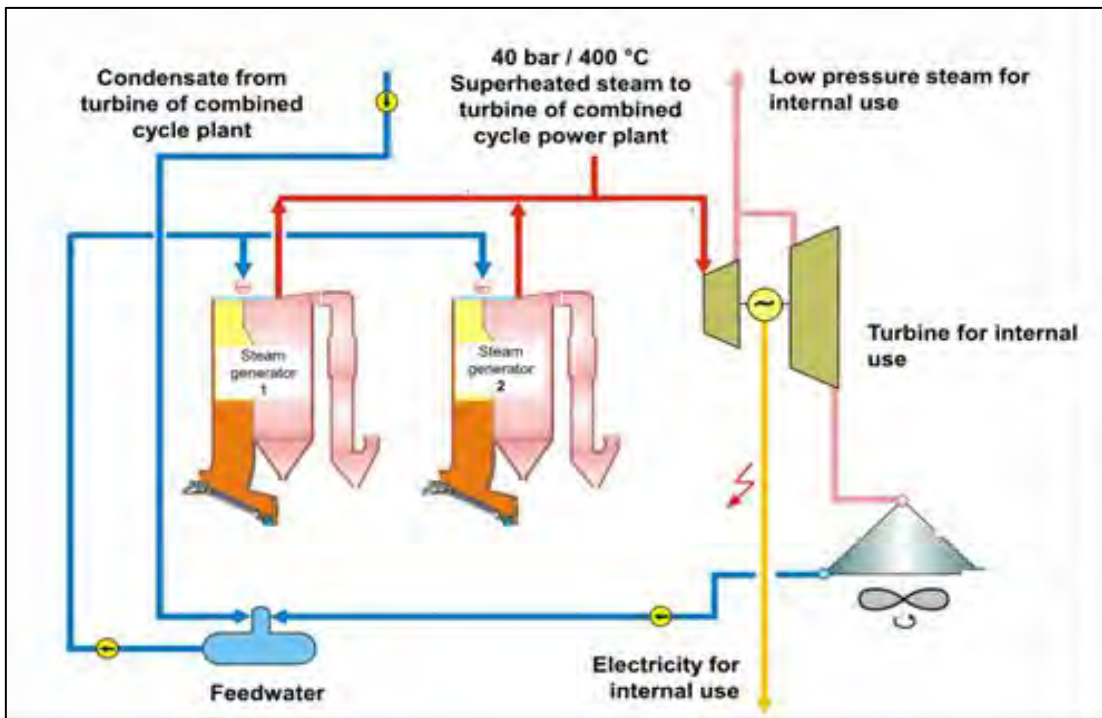
The heat released during waste combustion is converted to steam in 4-pass vertical steam generators, a small proportion of which is converted to electricity in a turbine to serve in-plant requirements.

It should be noted that this facility is designed to generate steam only as defined above. The conversion of the steam to electrical energy is carried out in the neighbouring 400 MW combined cycle power plant (CCPP) owned by Mainz-Wiesbaden AG.

Energy Production

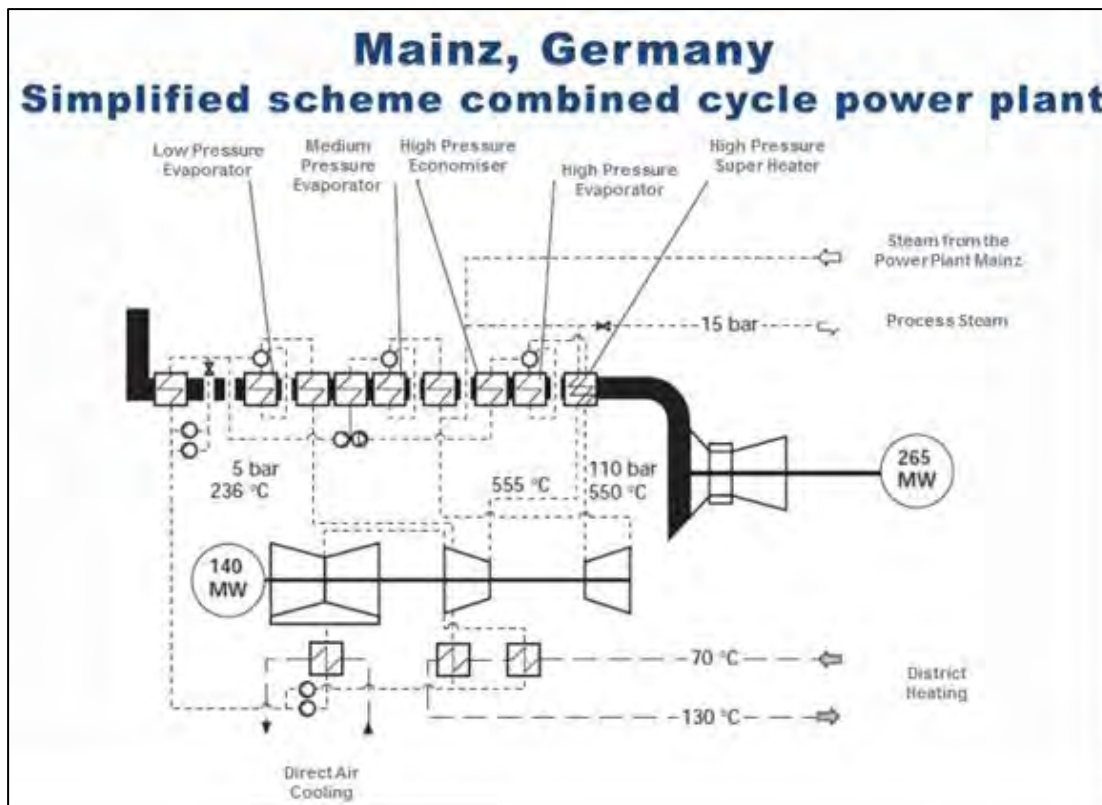
The majority of the steam produced in the Mainz facility is exported at 40 bar/400°C to the neighboring 400 MW CCPP owned by Mainz-Wiesbaden AG where the steam is superheated to 550°C without using additional primary energy sources and is converted to electricity in a highly efficient manner using a gas turbine. Based on data provided by MARTIN the net efficiency of this facility is >40%.

Figure 2-11-3: Schematic of the steam generators and integration with CCPP



Source: Martin GmbH, presentation entitled Mainz, Germany {provided directly by Martin}

Figure 2-11-4: Schematic of the waste to energy plant steam usage in the CCPP



Source: Martin GmbH, presentation entitled Mainz, Germany {provided directly by Martin}

Air Pollution Control

The flue gas cleaning systems consists of several highly-efficient cleaning stages, which either convert pollutants into air components or by adding chemicals like lime milk or activated coke, bind these pollutants in such a way that their reaction products can be carefully separated.

All emissions are measured at the stack at the end of the plant and clearly documented.

The plant is required not only to comply with the Federal German and European limits values (i.e. Waste Incineration Directive), but also the lower limit values stipulated in the permit issued by Struktur-und Genehmigungsdirektion Süd.

Table 2-11-4: The actual permitted and actual (2011) emission levels for the plant

| Parameter (Continuous Measurement) | 17 th BlmSchV (mg/m ³) | Actual Permitted Limits (mg/m ³) | Yearly Average Line 1 (mg/m ³) | Yearly Average Line 2 (mg/m ³) | Yearly Average Line 3 (mg/m ³) |
|--|---|---|---|---|---|
| Carbon Monoxide (CO) | 50 | 50 | 4.31 | 5.47 | 5.39 |
| Total Dust | 10 | 8 | 0.17 | 0.30 | <0.01 |
| Total Carbon | 10 | 10 | 0.34 | 0.24 | 0.01 |
| Hydrogen chloride (HCl) | 10 | 8 | <0.01 | 0.54 | 0.44 |
| Sulfur Dioxide (SO ₂) | 50 | 50 | 5.89 | 3.90 | 5.00 |
| Nitrogen Oxides (NO _x) | 200 | 150 | 114.22 | 117.41 | 117.42 |
| Mercury | 0.03 | 0.03 | 0.001 | 0.001 | 0.001 |
| Ammonia | - | 10 | 0.44 | 0.36 | 0.64 |
| Cadmium and Thallium | 0.05 | 0.05 | 0.0003 | 0.0002 | 0.001 |
| Total Antimony, Arsenic, Lead, Chromium, Cobalt, Copper, Manganese, Nickel, Vanadium and Tin | 0.5 | 0.5 | 0.028 | 0.03 | 0.04 |
| Total Arsenic, Benzo-Pyrene, Chromium (VI) | 0.05 | 0.05 | 0.002 | 0.006 | 0.001 |
| Dioxins and Furans (ng/Nm ³) | 0.1 | 0.08 | 0.002 | 0.002 | 0.005 |

Source: <http://www.mhkw-mainz.de/anlagentechnik/messwerte.php>

The flue gas cleaning systems consists of the following cleaning stages:

- SNCR unit (selective non-catalytic reduction) with aqueous ammonia injection into the first boiler pass above the furnace in order to reduce the nitrogen oxide emissions whilst forming air components, i.e. nitrogen gas and water vapour;
- High-dust catalytic converter to reduce surplus ammonia that has not reacted;
- Spray absorber with lime milk added via an atomiser wheel to reduce the temperature and pre-separation acidic flue gas components such as SO₂, HCl and HF;
- Facility for adding activated coke upstream of the fabric filters to bind dioxins/furans, heavy metals and other pollutants;
- Fabric filter for separating dust;

- Pre-scrubber with water injection to reduce acidic pollutants;
- Main scrubber with lime additive to remove residual flue gas components as well as mercury.

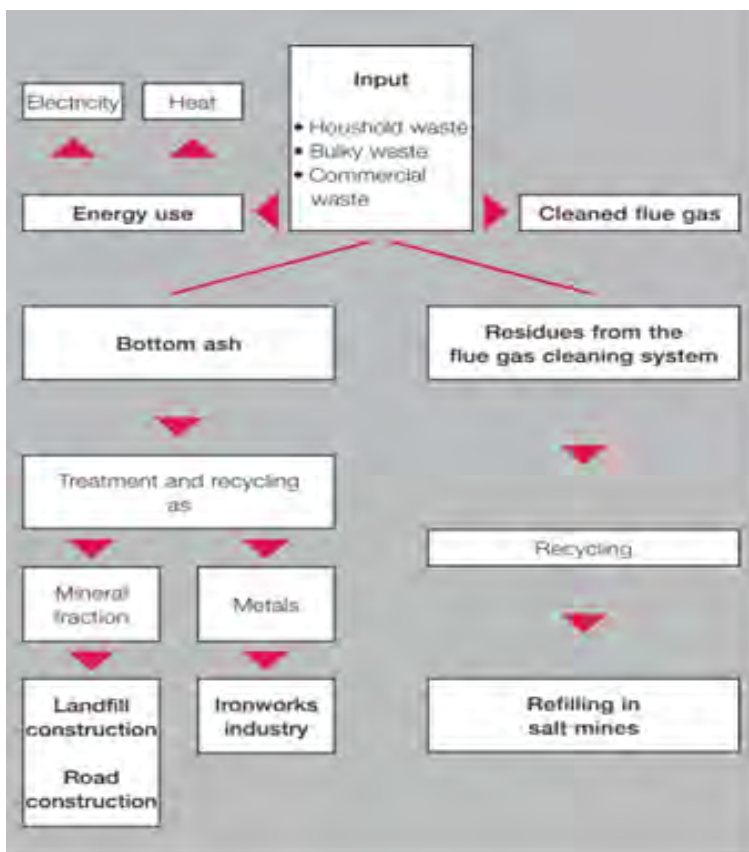
Continuous and intermittent measurements ensure that emission values are monitored and controlled at all times. Copies of the monitoring data can be obtained from Entsorgungsgesellschaft Mainz GmbH (mhkw-mainz) website (<http://www.mhkw-mainz.de/anlagentechnik/messwerte.php>).

Ash Handling and Processing

As a result of the incineration process approximately 26% of the input materials will become slag which will require further treatment.

The bottom ash is treated externally in a bottom ash treatment unit in a series of steps which separate the metal from the mineral fractions. Iron scrap and non-ferrous metals are recycled for use in the ironworks industry and the mineral fraction is used in landfill and road construction as substitute materials for virgin aggregates. Air Pollution Control (APC) residues are used for infilling old salt mines. The material flows through the process are summarised below:

Figure 2-11-5: Materials flows of the combustion residues



Source: www.mhkn.mainz.de/EGM_infobro3_eng_20.pdf

Plant Performance

MSW Processed

The plant has a maximum capacity of 340,000 tonnes per annum (1,100 tonne per day assuming 300 days of operation) with a calorific value of 7.5 to 14.0 MJ/kg. The residual waste treated at the facility has been collected from Mainz city and surrounding areas and other commercial sources.

All waste is transported to the facility using refuse collection vehicles.

Power and Heat Generation

The plant will generate the following heat outputs:

- Line 1 – 44MW
- Line 2 – 44MW
- Line 3 – 48MW

The adjacent CCPP generates 400MW electrical energy (not all sourced from the WtE facility).

Environmental Performance

Emissions to Air

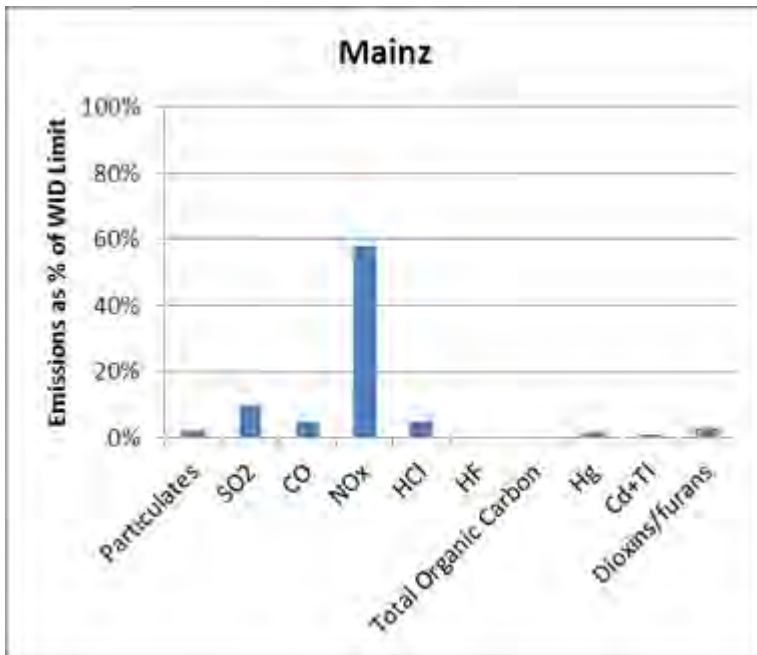
As described in the Air Pollution Control section above the emissions to air are minimised through a combination of high efficiency combustion within the furnace/boiler as well as by an efficient flue gas cleaning system.

All flue gases from each combustion train is continuously monitored for furnace temperature, opacity, CO, CO₂, SO₂, HCl, NO_x, and O₂.

The processes exhaust gases are emitted to the atmosphere via a 95m tall stack.

Based on emissions data for 2011 tabulated earlier in this case study the facility is producing significantly less emissions than permitted.

Figure 2-11-6: Emissions from the Mainz plant



Source: WSP analysis of plant data

Continuous emissions monitoring data can be obtained from Entsorgungsgesellschaft Mainz GmbH (mhkw-mainz) website (<http://www.mhkw-mainz.de/anlagentechnik/messwerte.php>).

Emissions to Water

No information available.

Emissions to Land

The solid residues of the thermal treatment process consist of 26% by weight of the waste processed and comprises bottom ash and air pollution control residues (including filters).

Ferrous and non-ferrous metals are removed from the bottom ash for recycling and the remaining mineral material is processed into aggregate for use in the construction industry.

Ferrous and non-ferrous metals are also removed from the APC residues, with the remaining materials being used to infill salt mines.

Footprint and Visual Impact

The total facility area is 160m x 70m x 46m.

No issues relating to the visual impact have been found. The site appears to be in an industrial zone adjacent to the Rhine, and an aerial view is shown below.

Figure 2-11-7: The Mainz Waste to Energy plant



Source: Martin GmbH

Operability, Reliability and Availability

Table 2-11-5: Performance data for the plant (2 lines) based on 2004 data

| Description | Lines 1 and 2 |
|-----------------------------|----------------|
| Time Available – Line 1 | 93.5% |
| Time Available – Line 2 | 94% |
| Parasitic Load (electric) | 18,000MWh |
| Quantity of Steam Generated | 768,620 tonnes |
| Steam Supply to Power Plant | 503,000 tonnes |
| Output | 7,834MWh |
| Gas Consumption | 1,812MWh |

| Description | Lines 1 and 2 |
|-----------------|---------------|
| Amount of Slag | 56,700 tonnes |
| Hazardous Waste | 8,667 tonnes |

(Source: Fischer, B (2005). Energieeffizienz des Müllheizkraftwerkes Mainz)

It can be seen from Figure 2-11-5 that both lines are achieving > 93.5% availability (> 8190 hours per year) of continuous operation.

Based on the data provided by the designer (Martin GmbH) the process is achieving an electrical conversion efficiency > 40%.

Economics

No information is currently available.

***The Mainz WtE plant is another example of a modern German plant producing high efficiency power and meeting stringent emission limits.
The plant also achieves high availability.***

Case Study 12 – Lahti II, Finland

Overview

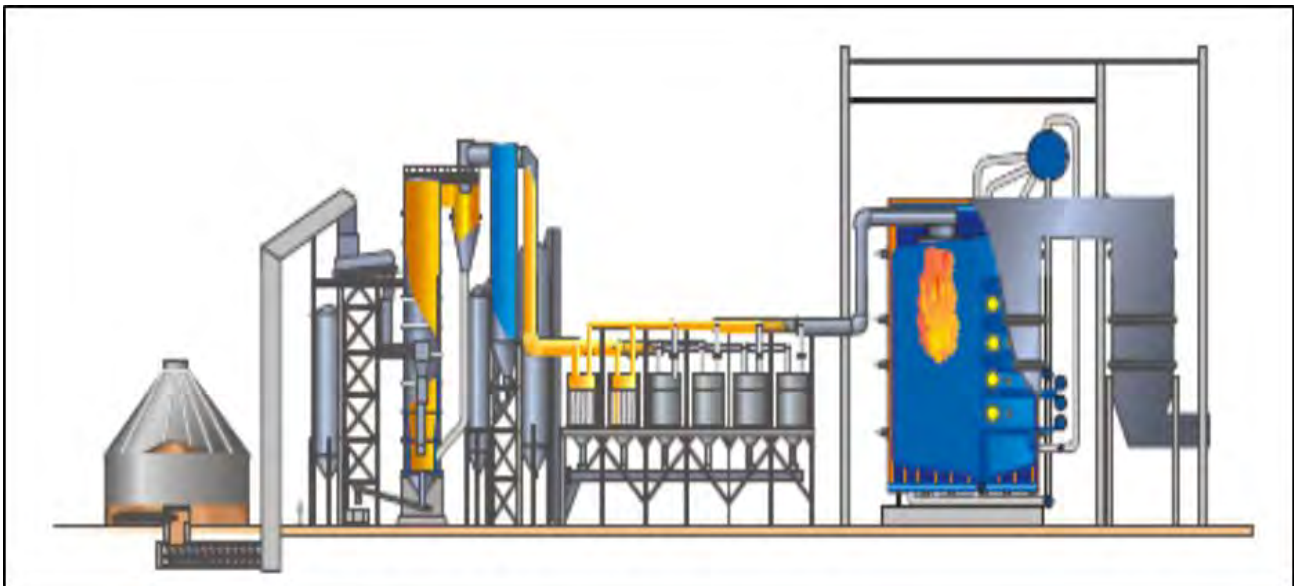
Metso, a well-known minerals and mining company acquired the fluidised bed combustion companies Tampella Power and Gotaverken Miljo in the 1990's and more recently they acquired the fluidised bed combustion division of Kvaerner Enviropower and formed Metso Power, based in Finland. The company has always been strong in FB gasification of biomass but has recently announced the development and construction of a circulating bed fluidised bed (BFB) gasifier for MSW/SRF applications.

Metso Power has many reference plants processing biomass that have operated for many years. The Lahti II plant is a CFB gasification plant built to process SRF with the following characteristics:

- The plant has been constructed on a greenfield site;
- The plant will process 250,000 tpa of SRF²⁴ in two lines;
- Two 80 MWth gasifiers producing 50 MWe and 90 MW of heat;
- Thermal efficiency calculated to be 31% (based on net waste CV);
- The heat recovery boiler operates at 121 bar and produces superheated steam at 540°C;
- Flue gas cleaning process includes: gas cooling and filtration by ceramic filters at 400°C; a dry APC²⁵ system and NOx control using SCR²⁶.

The Process

Figure 2-12-1: Schematic of the process layout at Lahti



Source: Metso Power

²⁴ Solid Recovered Fuel

²⁵ Air Pollution Control

²⁶ Selective Catalytic Reduction

Waste reception, storage and feeding

Waste is transported to the day silos which are located near the gasifier. From the fuel feeder the fuel is dropped through two rotary feeders to a fuel chute through which the waste passes into the CFB. The rotary feeders have air injection points in between them to prevent syngas flow backwards into the fuel silo.

The bed material is a mixture of sand and limestone, which is transported from the receiving silos into the CFB reactor by pneumatic conveying.

Gasification

The Metso Power solution includes a circulating fluidised bed (CFB) gasifier which processes the waste at temperatures of approximately 900°C. This process leads to the thermal decomposition of the input material creating a hydrocarbon rich synthesis gas (syngas) which then leaves the gasifier through a cyclone designed to recover particulate matter.

The syngas generated needs to be cleaned to remove certain contaminants. Once the gas has been cooled in a Heat Recovery Unit (HRU) to approximately 400°C, it is passed through a series of hot gas ceramic filters which remove heavy metals and any residual particulate matter. The residues extracted from the gas contain carbon, chlorine and calcium oxide and are disposed of separately.

Energy Production

The final stage of the process is the generation of high temperature and pressure steam. Once cleaned, the syngas has few corrosive contaminants enabling a customised boiler developed by Metso Power to operate at higher temperatures (540°C) than conventional waste boilers. These conditions, together with re-use of the heat extracted by the HRU when cooling the gas coming out of the gasifier, lead to a high thermal efficiency process. The steam is then used in a conventional steam turbine to generate power.

Air Pollution Control

The flue gas cleaning system consists of selective catalytic NO_x reduction (SCR) and a bag house filter with additive injections. Ammonia water solution is brought into contact with the flue gas after the gas boiler at a flue gas temperature of approximately 300-400°C. The flue gas passes through a catalyst, on the surface of which NO_x and NH₃ molecules are converted into molecular nitrogen and water.

After the heat exchangers the flue gas is conveyed to a bag house filter consisting of two cylindrical filter modules. Particles in the flue gas are deposited on the external surface of filter bags assembled vertically inside the modules. In order to absorb acid gases (SO₂, HCl and HF) in the flue gas, sodium bicarbonate is injected upstream of the filter. Activated carbon can also be injected to control the emissions of gaseous heavy metals, dioxins and furans. Thus, the layer of dust on the bags, the filter cake, consists mainly of additives and solid reaction products. The chemical reactions that capture pollutants from the flue gas continue in the filter cake as flue gas passes through. The dust layer also improves mechanical separation of particles from the flue gas.

The filter bags are periodically cleaned (on-line) with pulses of low pressure cleaning air. Air is produced by a dedicated compressor included in the filter supply. Bag cleaning is controlled by a PLC²⁷ and the cleaning frequency can be based on a timer and / or the pressure difference across the filter. Cleaning of the bags is performed gradually in order to minimize the number of bags with reduced filter cake layer. As a result, the overall efficiency of the bag house filter remains stable.

²⁷ Programmable Logic Controller

During cleaning, the dislodged filter cake falls to the flat bottom of the filter module. The bottom is equipped with a slowly rotating scraper to move gathered fly ash to the bottom outlet. From the outlet, fly ash is removed by discharge screws and pneumatic transmitters to the fly ash silo. The filter bottom is furnished with trace heating to be used during process stop situations to prevent the bottom from cooling down.

Ash Handling and Processing

Coarse non-combustible material is removed from the CFB reactor through a vertical ash chutes. From these chutes the bottom ash is transported by a water cooled ash screw and by a water cooled drag chain conveyor into the containers. The ash container is exchanged for an empty one and removed from site to landfill disposal.

Plant Performance

The Metso Power gasification plant at Lahti in Finland has been included in the state-of-the-art case study because it is the first and largest gasification plant processing MSW-derived RDF in the world. Consequently, in our opinion it is an extremely important development in respect of Advanced Thermal Conversion technologies.

However, because the plant has only been operating since the beginning of 2012 it has not operated for a full year and therefore does not have suitable data that can be reported here. This section of the case study is therefore less comprehensive than many of the other case studies.

MSW Processed

The plant has been constructed as two lines, each capable of producing 80 MWth of energy output and processing 125,000 tpa of RDF. We understand that the plant has processed more than 100,000 tpa of waste so far this year.

WSP has visited the plant and can report that it is very impressive, well engineered and operating to its design conditions. The plant did experience an unscheduled outage during our visit which was caused by a leak in the ceramic filters.

Power and Heat Generation

The plant is designed to produce 50 MWe and 90 MW of heat for district heating developing a net conversion efficiency of 31%.

Environmental Performance

Emissions to Air

No emission data is available at this time but the plant has been designed to meet the emission limits for air pollution set by the EU WID and during our visit to the plant we were informed that no exceedances of pollutant emissions to air had been experienced to date.

Emissions to Water

The process employs dry gas cleaning processes and therefore minimal liquid effluent emissions occur.

Emissions to Land

The solid residues produced by the process include bed ash and filter ash (fly ash) and the quantities will depend on the ash content of the waste feed material. The bed ash would be landfilled and the fly ash treated as a hazardous waste and handled and managed in a safe and environmentally conscious manner.

Footprint and Visual Impact

The plant is reported to require 25 m² per 1,000 tpa of waste processed.

The visual impact of the gasification plant is similar to many EfW facilities but, in this case, the plant is built alongside a much larger coal-fired power plant. The building is taller because the circulating fluidised bed requires a greater height for the freeboard section of the plant.

Operability, Reliability and Availability

Until October 2012 the gasification plant has operated for about 3,000 hours giving a total operational track record of ca. 6,000 hours (two lines).

The main operational disturbances at the Lahti Energia plant during its first year of operation were reported to WSP during our visit:

- Gasifier waste feeding trips have occurred due to rotary valve blockages caused by oversized metals in the waste fuel. The fuel feeding system has been modified during the planned shutdown in September 2012. Also the fuel yard system has been modified by the owner to take out extraneous metals prior to the gasifier feed system.
- The hot gas filters have experienced a few candle filter element breakages in the hot gas clean-up system resulting in unscheduled plant trips. We understand the cause of the problem has been identified and resolved.
- Tar condensation has occurred in few places, which will be solved by additional insulation.

Economics

No cost data is currently available for this technology. However, information WSP has seen in relation to a confidential feasibility study indicates that the cost of the process is competitive with alternative thermal treatment technologies.

The CFB gasification plant developed by Metso Power for the processing of RDF/SRF is a state-of-the-art development; which, in our opinion will change the waste management landscape with respect to how gasification is perceived and utilised.

Case Study 13 – Montgomery County, Maryland, USA

Overview

The Energy from Waste facility at Dickerson, Maryland (the Montgomery County Resource Recovery Facility) which is owned by Northeast Maryland Waste Disposal Authority and is operated by Covanta Montgomery Inc. (a fully owned subsidiary of Covanta Holding Corporation) under a 20 year Service Agreement. The Montgomery County Resource Recovery Facility is built adjacent to the Dickerson Generating Station which is an 853MW fossil fuel electrical generating plant.

The Montgomery County Resource Recovery Facility can process 1,830 tonnes per day (572,273 tonnes per year) through three 610 tonnes per day waterwall furnaces and covers an area of approximately 14 hectares.

All waste processed at the site is initially transported to the Shady Grove transfer station in Derwood where it is compacted into intermodal steel waste containers and then loaded onto railcars for delivery to the facility. Covanta state that this unique rail system (in the USA) allows the county to virtually eliminate traffic on the rural road leading to the facility.

The plant was fully commissioned in August 1995 at a cost of approximately \$160million and treats municipal waste from up to 24 communities in South Central part of Maryland County.

Permits for the facility, which were granted by the Department of Environmental Resources (DER) in July 1987, were subsequently challenged by a Plymouth Township citizen's group opposed to the incinerator. The hearing board took 16 months to rule that DER issued the permits correctly.

Key outputs are as follows:

- The turbine generators rated capacity is 63MW. Net production of up to 55MW which is sold into the PJM system.
- The processes exhaust gases are emitted to the atmosphere via an 84 metre stack.
- The composition of the gases generated in each of the combustion units are sampled every ten seconds. The Montgomery County Resource Recovery Facility must comply with the requirements of Maryland Department of the Environment (MDE) Permit #24-031-01718, as well as Federal standards. Under this air quality permit, the following limits must not be exceeded:

Table 2-13-1: Permitted limits for the Montgomery County plant

| Parameter | MDE Permit Requirements | Federal Standards (40 CFR 60) |
|----------------------|---|---|
| Opacity | No visible emissions other than water in an uncombined form. | 10% (6 minute average) |
| Carbon Monoxide (CO) | 200 ppmv @ 7% O ₂ , dry (1 hour average) 50 ppmv @ 7% O ₂ , dry (24 hour average) | 100 ppmv @ 7% O ₂ , dry (4 hour average) |
| | EU WID limits mg/Nm³ @ 11%O₂ dry 50 ppmv = 44.6 mg/Nm ³ 200 ppmv = 178.5 mg/Nm ³ | EU WID limits mg/Nm³ @ 11%O₂ dry 100 ppmv = 89.2 mg/Nm ³ |

| Parameter | MDE Permit Requirements | Federal Standards (40 CFR 60) |
|------------------------------------|--|--|
| Hydrogen Chloride (HCl) | 25 ppmv @ 7% O ₂ , dry (3 hour average) or ≥95% removal efficiency | 29 ppmv @ 7% O ₂ , dry or ≥95% removal efficiency |
| | EU WID limits mg/Nm³ @ 11%O₂ dry 25 ppmv = 29.1 mg/Nm ³ | EU WID limits mg/Nm³ @ 11%O₂ dry 29 ppmv = 33.7 mg/Nm ³ |
| Sulfur Dioxide (SO ₂) | 30 ppmv @ 7% O ₂ , dry (3 hour average) or ≥85% removal efficiency | 30 ppmv @ 7% O ₂ , dry (24 hour average) or ≥75% removal efficiency |
| | EU WID limits mg/Nm³ @ 11%O₂ dry 30 ppmv = 61.2 mg/Nm ³ | EU WID limits mg/Nm³ @ 11%O₂ dry 30 ppmv = 61.2 mg/Nm ³ |
| Nitrogen Oxides (NO _x) | 180 ppmv @ 7% O ₂ , dry (3 hour average) | 180 ppmv @ 7% O ₂ , dry (3 hour average) |
| | EU WID limits mg/Nm³ @ 11%O₂ dry 180 ppmv = 252.4 mg/Nm ³ | EU WID limits mg/Nm³ @ 11%O₂ dry 180 ppmv = 252.4 mg/Nm ³ |

- Covanta have provided a summary of Compliance Monitoring and Testing for Direct Comparison to Ontario Guideline Requirements attached at Appendix 1. The real time emissions and archived data can also be obtained from the Counties website.
- In fiscal year 2009, ash generation, which includes a small amount of reagent addition for pollution control was 29.5% by weight of the waste processed.
- Following treatment approximately 12,000 (2.4% by weight of the waste processed) tons of ferrous metal is removed from the ash annual and reprocessed. The remaining ash is loaded into sealed containers and transported by rail to a landfill in southern Virginia where it is beneficially used as road bed material.
- Gross electricity generation for fiscal year 2009 was 352,000 MWh or 655 KWh per tonne processed.

Suppliers involved in the Project:

- Boilers - Distral Energy Corporation Boiler equipped with natural gas burners and lance and stationary rotary soot blowers
- Grate – Martin Reverse-Reciprocating Stoker
- Turbine/Generator – General Electric

The Process

Waste reception, storage and feeding

All waste is brought to the tipping floor by rail in totally contained rail containers on tipping chassis. Up to five trucks shuttle containers from the railyard to the tipping floor and deposit the waste into the waste pit/bunker. Prior to entering the tipping floor each containers passes through a Bicon radiation detector, if an alarm is triggered an operative use a hand held Bicon Fieldspec multichannel analyser to identify the specific isotope and level to determine if the load is safe to deposit into the refuse pit/bunker.

Because the waste containers are totally enclosed until they get inside the tipping floor building, the facilities grounds are very clean and free from litter, requiring minimal policing of the grounds.

The tipping floor has two overhead cranes to feed the waste in the hoppers of the three combustion units. Each crane has a grapple capacity of five tons.

Primary combustion air is drawn from the tipping floor to form negative pressure in the tipping floor building.

Combustion

The Montgomery County Resource Recovery Facility uses three parallel combustion trains, each designed to process 600 tonnes per day of municipal solid waste with an energy value of 5,500 BTU's per pound [12.78 MJ/kg]. Waste moves by gravity and agitation on top of a downward sloping grate system. The grate system is a patented technology composed of alternating rows of fixed and moving grate bars, known as the Martin Reverse-Reciprocating Stoker.

A forced draft fan supplies the primary combustion air underneath the grate.

The Montgomery County Resource Recovery Facility was also the first publicly owned facility to incorporate Covanta's LN (Low NOx) technology. Stage combustion is accomplished by secondary air injection through the front and rear walls of the furnace just above the grates, while tertiary air is injected much higher in the firebox. Air pre-heaters exist to add additional drying capability using turbine exhaust steam to raise underfire air temperatures.

Above each grate system is a Distal Energy Corp. single drum natural circulation steam generation boiler designed to generate 171,000 pounds of steam per hour [77,634 kg/hr steam] at 865 psig [59.6 barg] and 830°F [443°C]. The boilers are equipped with natural gas burners capable of heating the boilers during startup and maintaining permitted temperature requirements during combustion upsets. Both lance and stationary rotary soot blowers are used to clean the boiler tubes twice a day.

Water is supplied to the boilers using either two electric or one steam driven boiler feedwater pumps.

Energy Production

Steam from the boilers is used to operate a General Electric turbine generator set complete with main condenser, steam jet are ejectors, and oil lubricating system. The rated capacity of the generator is 74MW. At 100% design conditions the facility generates up to 63MW depending on whether air pre-heaters are steam driven boiler feed pumps are running. Up to 55MW of electricity is sold into the grid system.

Gross electricity generation for fiscal year 2009 was 352,000 MWh or 655 KWh per tonne processed.

Air Pollution Control

Following commissioning in 1995 and in response to significant reductions in permitted air emission following changes to Federal Legislation the air pollution control systems were upgraded to ensure compliance.

Air pollution is minimised by high efficiency combustion within the furnace/boiler as well as by Covanta's LoNOX process. Air pollution equipment for each independent train subject flue gases to several pollution control devices designed to remove metals, acid gases, nitrous oxides and particulate materials prior to the gases being exhausted to air via a common stack.

A thermal DeNOx system uses aqueous ammonia to remove nitrous oxides without ammonia slip. A hydrated lime injection system and a spray dryer absorber removes acid gases such as sulphur dioxide and hydrogen chloride. A carbon injection system removes mercury vapours, dioxins and furans. At the end of the air pollution controls are a series of baghouse cells which remove 99.9% of particulates matter entrained in the flue gas.

Continuous monitoring equipment is located throughout the boiler and air pollution control equipment to ensure compliance with permitted conditions. Each combustion train is continuously monitored for furnace temperature, opacity, CO, CO₂, SO₂, HCl, NOx, O₂ and exhaust gas volumetric flow.

Ash Handling and Processing

As a result of the incineration process a proportion of the input materials will become ash which will require further treatment.

Fly ash collected from the air pollution control equipment and boilers is transported by enclosed screw conveyors to fugitive emissions. The fly ash is mixed with the bottom ash in a water bath ash discharger. Fly ash is also mixed with a controlled amount of dolomitic lime to prevent the leaching of heavy metals from the ash. A ram pushes the combined ash out of the water bath on a vibrating pan conveyor which transports the ash to an ash storage pit. Overfire combustion air is taken from the ash pit to keep it under negative draft to control fugitive emissions.

The ash is moved by overhead cranes to a grizzly separator which removes oversized items larger than 10 inches [25.4 cm]. The oversized items are further sorted to maximise recycling of ferrous metal and organic fractions where they existing in large enough quantities.

The ash is then loaded into sealed rail containers and transported to an appropriate landfill site where it is beneficially used as road bed material.

Plant Performance

MSW Processed

The MSW treated at the facility has been collected from households and premises where recyclable materials have already been segregated and additional segregation of ferrous metals occur at the site following shredding prior the waste being introduced into the combustion chamber.

All waste is transported to the facility via rail from the central transfer staff located at Derwood in sealed intermodal containers which significantly reduces transportation impact on the immediate locality.

Power and Heat Generation

The plant generates approximately 63MW of electricity of which 55MW is exported to the local supply network.

Gross electricity generation for fiscal year 2009 was 352,000 MWh or 655 KWh per tonne processed.

No data relating to heat capacity could be obtained.

Environmental Performance

Emissions to Air

As described in the Air Pollution Control section above the emissions to air are minimised through a combination of high efficiency combustion within the furnace/boiler as well as by Covanta's LoNOx and the use of efficient flue gas cleaning technologies.

All flue gases from each combustion train is continuously monitored for furnace temperature, opacity, CO, CO₂, SO₂, HCl, NOx, O₂ and exhaust gas volumetric flow.

The processes exhaust gases are emitted to the atmosphere via an 84 metre stack.

In fiscal year 2009 the facility reported emitting:

- NOx: 563 tonnes, or 1.07 tonnes per 1,000 tonnes processed.
- Acid gases (sulphur dioxide and hydrogen chloride): 195 tonnes, or 0.37 tonnes per 1,000 tonnes processed.
- Dioxins and furans: <0.005 kg.
- Mercury: 17 kg.

Table 2-13-2: Emissions testing data for 2005 and 2006

| Compliance Test Year-Unit | Particulate (mg/dscm ³) and Metals (ug/dscm ³) | | | | | | Acid Gases as ppm _{vdv} ⁷ | | | | | | Combustion as ppm _{vdv} ⁷ | | PCDD/PCDF | |
|---|--|--------------------|-------|--------------------|--------------------|--------------------|---|---------------------|-------|-----------------|---------------------|------|---|------|----------------------------|-------------------------------|
| | Hg | | | Cd | Pb | PM | HCl | | | SO ₂ | | | NOX | CO | TE as pg/dscm ³ | Total as ng/dscm ³ |
| | In | Out | % | | | | In | Out | % | In | Out | % | | | | |
| 2005-1 | 289 | 3.71 | 98.7 | 0.267 | 6.17 | 2.57 | 643 | 5.81 | 99.1 | 233 | 12 | 95 | 169 | 14 | 16.8 | 1.07 |
| 2005-2 | 240 | 4.82 | 97.9 | 0.434 | 5.2 | 2.14 | 534 | 4.94 | 99.1 | 216 | 14 | 94 | 170 | 17 | 9.4 | 0.806 |
| 2005-3 | 152 | 6.38 | 95.8 | 0.85 | 11.2 | 2.11 | 897 | 8.21 | 98.8 | 214 | 16 | 93 | 169 | 16 | 7.5 | 0.605 |
| Average | 227 | 5.0 | 97.47 | 0.52 | 7.52 | 2.27 | 625 | 6.3 | 99.00 | 221 | 14 | 94 | 169 | 16 | 11 | 1 |
| 2006-1 | 191 | 7.93 | 95.5 | 0.934 | 35.7 | 5.8 | 568 | 14.3 | 97.5 | 202 | 9 | 95.8 | 170 | 15 | 29 | 1.87 |
| 2006-2 | 161 | 10.2 | 93.6 | 0.426 | 8.72 | 4.31 | 579 | 15.5 | 97.3 | 194 | 10 | 94.8 | 170 | 21 | 16.9 | 1.14 |
| 2006-3 | 180 | 14.3 | 92 | 0.703 | 11.9 | 4.85 | 652 | 17.7 | 97.3 | 193 | 13 | 93.3 | 170 | 21 | 60.5 | 3 |
| Average | 177 | 10.8 | 93.7 | 0.69 | 18.77 | 4.99 | 600 | 15.8 | 97.4 | 196 | 11 | 95 | 170 | 19 | 35 | 2 |
| Local Regulatory Compliance Level | None | 80 | 85 | 40 | 440 | 27 | None | 25 | 95 | None | 29 | 75 | 180 | 100 | None | 30 |
| Local Regulatory Compliance Level Converted to Ontario Guideline Units | None | 57 | 85 | 29 | 314 | 19 | None | 18 | 95 | None | 21 | 75 | 128 | 71 | None | 21 |
| Ontario Guideline A-7 | None | 20 | None | 14 | 142 | 17 | None | 18 | 95 | None | 21 | None | 110 | None | 80 | None |
| Ontario Guideline Units(2) | NA | mg/Rm ³ | NA | ug/Rm ³ | ug/Rm ³ | mg/Rm ³ | NA | ppmdv ¹¹ | % | NA | ppmdv ¹¹ | NA | ppmdv ¹¹ | NA | pgm ³ (3) | N/A |
| 2005 Emissions converted to Ontario Guideline Units | NA | 3.5 | NA | 0.37 | 5.37 | 1.62 | NA | 4.5 | 99.0 | NA | 10.0 | NA | 121 | 11 | 8 | N/A |
| 2006 Emissions converted to Ontario Guideline Units | NA | 7.7 | NA | 0.49 | 13.40 | 3.56 | NA | 11.3 | 97.4 | NA | 7.6 | NA | 121 | 14 | 25 | N/A |

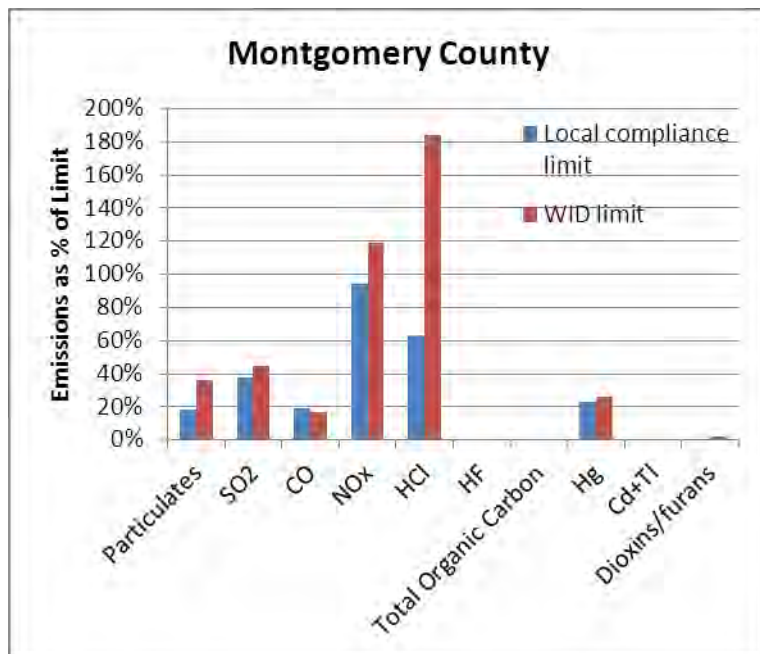
Notes:

(1) All US emissions are corrected to 7% O₂

(2) All Ontario Guideline limits are corrected to 11% O₂

(3) Toxic equivalence factor recommended by NATO in 1989, adopted by Canada in 1990.

Figure 2-13-1: Emissions performance of Montgomery County WtE plants versus local and EU regulatory limits



Source: WSP analysis of data from Table 2-13-2

It is clear that as a state-of-the-art WtE plant in a US context Montgomery County meets the local regulatory emissions limits (blue bars) but the plant would not meet the EU limits for HCl and NOx. The flue gas cleaning system could be optimised to do this but would require additional capital and operating costs.

We understand that in the past 10 years of operation (to 2009) no notices of violation have been received. This is credited to the fact that they operate an automated predictive alarm system that monitors continuous emission monitoring data to determine if permit levels are likely to be exceeded.

Continuous emissions monitoring data can be obtained from Montgomery County:

http://www6.montgomerycountymd.gov/swstmpl.asp?url=/content/dep/solidwaste/facilities/rff_cemdata.asp .

It is also worthy of note that as all waste is delivered to site and ash is removed by rail, this reduces truck traffic by 28,000 trips per year. This means that the expected source of air emissions from vehicles has been eliminated.

Emissions to Water

Unlike most Waste to Energy facilities, the Montgomery County Resource Recovery Facility is located adjacent to a power plant. Rather than taking river water directly from the Potomac River, the facility draws its process water needs from the cooling waste discharge canal of the power plant who extracts water from the river.

The facility draws about 890,000 gallons [3.37×10^6 litres] of waste per day which supplies 100% of the needs of the plant. About 10% of the water intake is discharged back into the power plants discharge channel.

Emissions to Land

The solid residues from the thermal treatment process comprise 29.5% by weight of the waste processed and include bottom ash and air pollution control residues (including filters).

Fly ash collected from the air pollution control equipment and boilers is transported by enclosed screw conveyors to fugitive emissions. The fly ash is mixed with the bottom ash in a water bath ash discharger. Fly ash is also mixed with a controlled amount of dolomitic lime to prevent the leaching of heavy metals from the ash. A ram pushes the combined ash out of the water bath on a vibrating pan conveyor which transports the ash to an ash storage pit. Overfire combustion air is taken from the ash pit to keep it under negative draft to control fugitive emissions.

The ash is moved by overhead cranes to a grizzly separator which removes oversized items larger than 10 inches [25.4 cm]. The oversized items are further sorted to maximise recycling of ferrous metal and organic fractions where they existing in large enough quantities.

The ash is then loaded into sealed rail containers and transported to an appropriate landfill site where it is beneficially used as road bed material.

Footprint and Visual Impact

Figure 2-13-2: Photograph of the Montgomery County WtE plant



Source: Covanta

The total site area is approximately 14 hectares.

During 1997 and later in 2003, Montgomery County Government's Department of Environmental Protection did a study of lighting impacts of the facility. It was observed that the facility has made significant efforts to eliminate off-site lighting impacts through good site lighting design and operating procedures and that any additional attempts to darken the facility will produce only limited perceptions of change but may present safety concerns.

Operability, Reliability and Availability

WSP requested recent availability data for the Montgomery County facility from Covanta Energy but none was provided before this report was published.

Historic data presented in a paper by Lehr, Licata and Terracciano gives annual operation hours for the facility from 1992 – 1999. The % availability ranged from 90 – 91.9 for boiler #1 and 90 – 91.5 for boiler #2. The

average availability was 90.64% for boiler #1 and 90.31% for boiler #2. It is clear that the plant operated with good availability for the eight year period in question and we have no reason to doubt that the plant continues to achieve similar statistics today.

Economics

For Fiscal year 2009:

- Cost of operating the plant - \$30.8 million
- Gross Electrical generation was 352,000 MW_e – total sales \$22.4 million
- Sale of ferrous metal – total sales \$1.4 million
- Cost per ton (excluding finance costs) - \$15 per ton [\$14.76 per tonne].

Although the Montgomery County Resource Recovery Facility in Maryland, USA is a relatively old plant it has been included as a case study for the following reasons:

- *modern moving grate combustors have been added to improve efficiency;*
- *the Covanta LN process has been retro-fitted to significantly improve the de-NO_x capability of the plant;*
- *the plant achieves good emission control and meets the local regulatory requirements;*
- *the facility has undergone a significant health impact assessment;*

The plant, however, would not meet the EU emission limits for HCl and NO_x without additional mitigation measures via flue gas cleaning system upgrades.

Case Study 14 – Japanese Slagging Gasification

Preamble

Many commentators consider gasification of waste to be unproven - they could not be more wrong. The Japanese have embraced gasification technologies for the processing of waste derived fuels, such as MSW, C&I, RDF and ASR²⁸. We will provide an overview of the current situation of slagging gasification and brief technical reviews of the leading companies.

Overview

Much of the interest around the world in waste gasification over the last fifteen years has originated with political decision makers seeking an alternative to incineration that achieved the following objectives, in order of political priority:

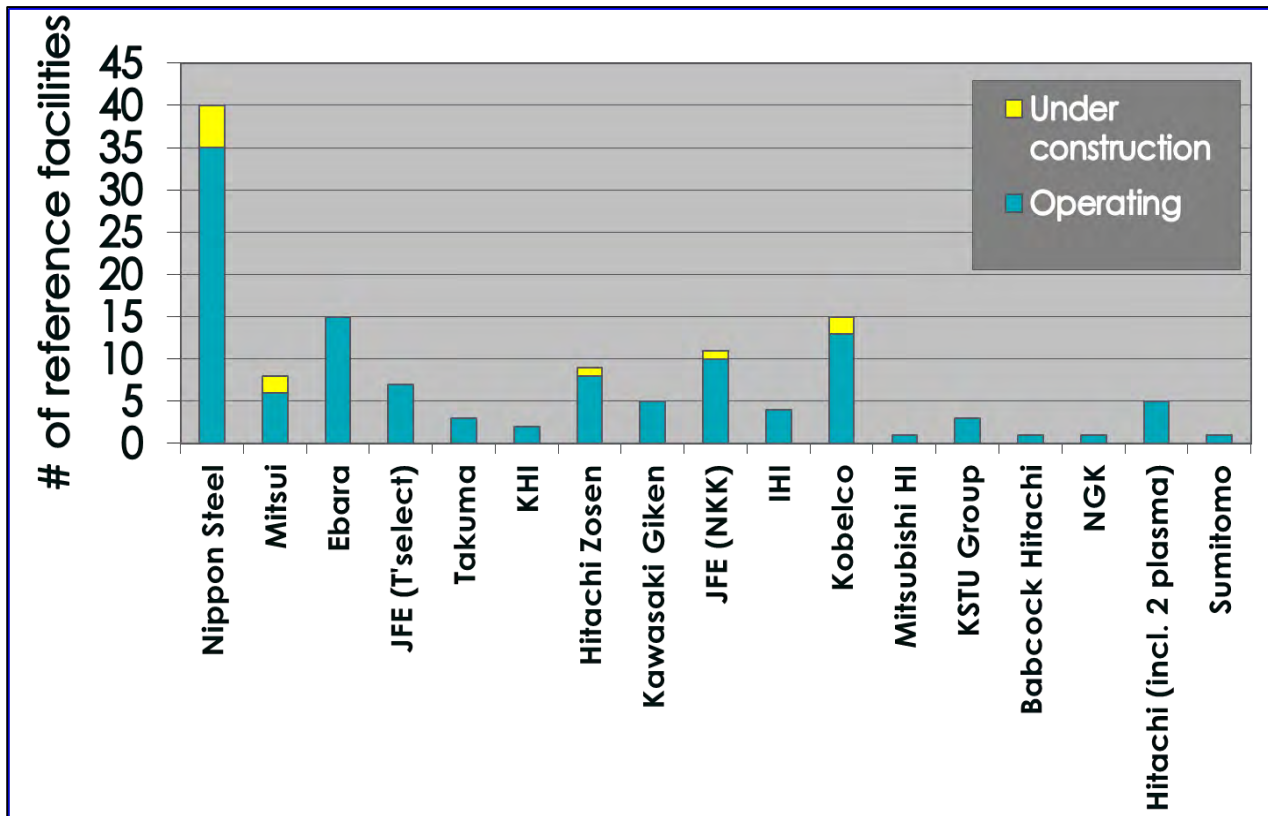
- produced demonstrably low emissions – particularly of dioxins;
- provided better resource recovery, in the form of materials and energy that could be re-used;
- is fully proven at commercial scale.

Over the last few years, the perception has arisen in Europe, Australia and parts of North America that gasification has failed against these objectives; principally because of the poor operational track record of gasification processes developed by smaller lowly capitalised companies. Waste gasification technologies developed in Japan are proof that this is a misconception. In WSP's view, the majority of the processes operating in Japan deliver on each of those three key objectives:

- the reference plants have low emissions, particularly of dioxins;
- they do recover materials which have found viable and useful applications; and
- they are proven and therefore 'bankable' at least in a Japanese context, although it should be noted that the leading suppliers of slagging gasification technologies are actively seeking opportunities outside of their home markets.

²⁸ Auto Shredder Residue

Figure 2-14-1: The number of waste slagging gasification processes in Japan



Source: WSP analysis

The above chart shows that there are 122 operating waste slagging gasification plants processing 6,915,870 tonnes per year of MSW/RDF. There are also nine plants under construction which will process a further 1,047,300 tonnes per year of MSW/RDF.

There are many Japanese companies that have licenced or developed technologies and have constructed gasification plants. We will focus on the leading six companies in this review and provide a brief overview of each:

- Nippon Steel;
- Kobelco-Eco;
- JFE;
- Hitachi Zosen;
- Ebara;
- Mitsui Engineering & Shipbuilding.

There is more data available from some of these companies than others and therefore the reviews will vary in length. We have much more data for the Nippon Steel DMS technology and that review will give an indication of what has driven the Japanese government to favour this type of gasification technology over recent years. There is evidence, however, that over the past couple of years new EfW projects in Japan are favouring conventional combustion technologies again.

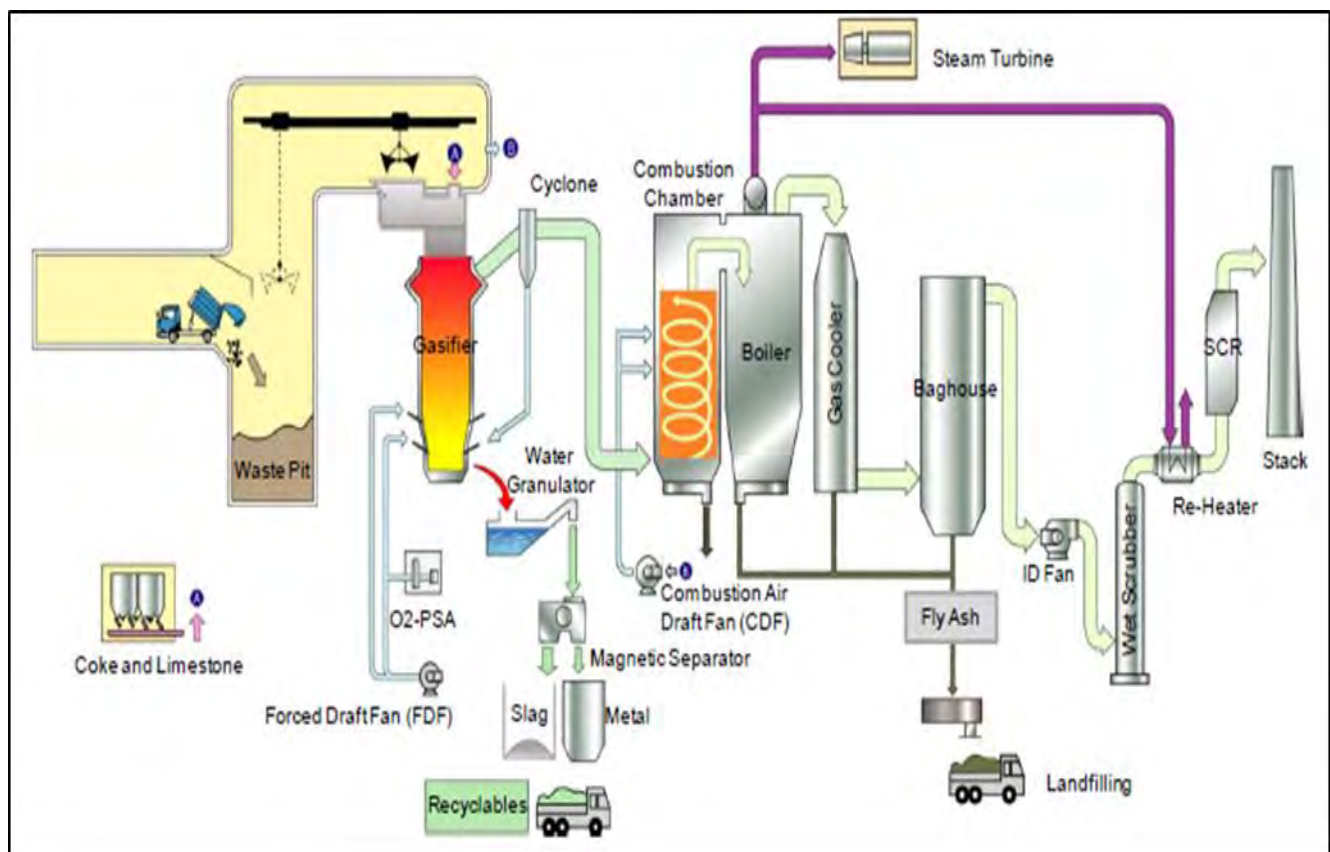
Nippon Steel

Nippon Steel are the largest supplier of gasification plants in Japan with 35 operational plants in total, 33 in Japan and 2 in South Korea, of which the Shin-Moji (Kitakyushu) plant is the largest.

The technology is based on a fixed bed, updraft, shaft-type gasifier. The process differs from conventional gasification by the addition of the ash melting stage. Coke and limestone are introduced to the gasifier along with the waste, and fall to the base of the bed along with residual char. Oxygen-enriched air is introduced to the bottom of the bed which reacts with the coke to produce very high temperatures up to 1,800°C. As well as providing the necessary heat to drive the gasification reactions to produce syngas in the middle section of the reactor, inorganic material (ash and metals) is melted and collected at the bottom. Syngas driven off is immediately transferred to a combustion chamber where it is combusted and the hot flue gases passed through a boiler to raise steam to drive a turbine generator which produces electricity.

The plant maximises recycling and is capable of treating a wide range of wastes that would not be possible to treat via conventional incineration or gasification, such as landfill minings, incinerator bottom ash and sewage sludge. Energy recovery performance is relatively poor compared to conventional incineration due to the requirement for secondary fuel and high parasitic electricity demand. However, the driver for thermal waste treatment in Japan is to minimise landfill and maximise resource recovery, and unlike many other regions (such as Europe) energy recovery is a secondary consideration.

Figure 2-14-2: Process flow diagram for the Nippon Steel DMS process

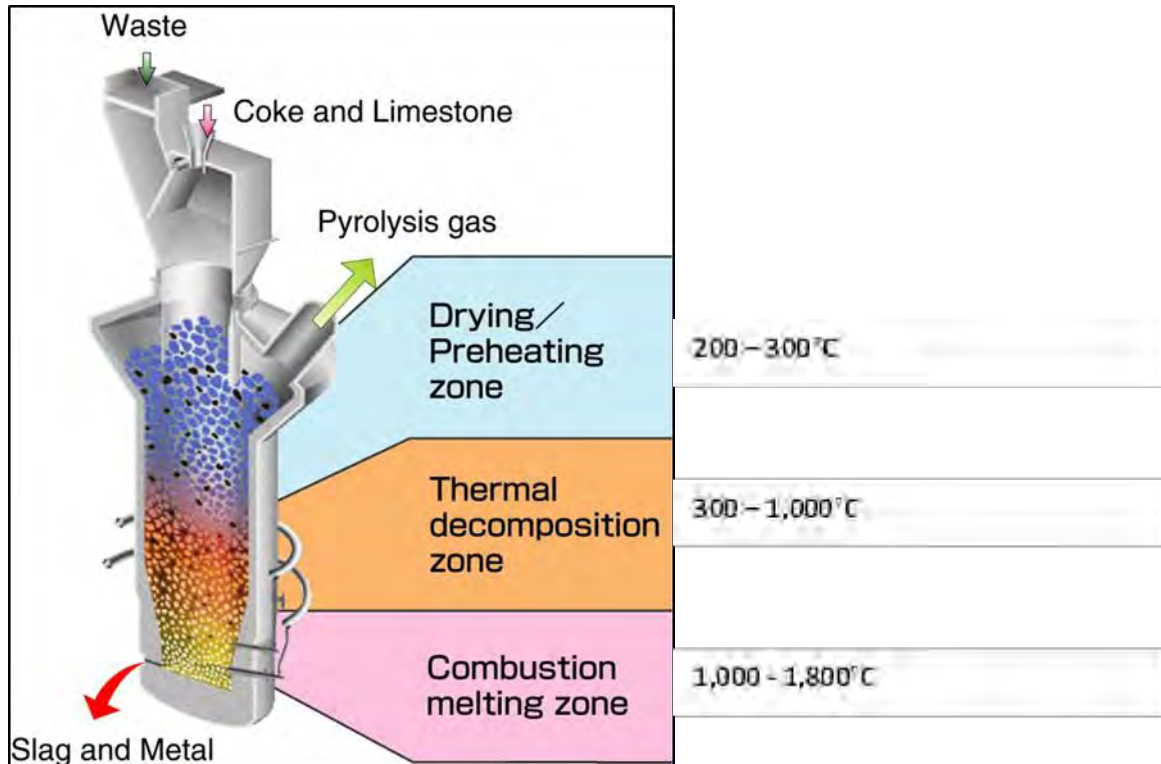


Source: Nippon Steel

Waste is fed into the top of the gasification and melting furnace, along with coke and limestone. The furnace is a relatively simple updraft gasifier. Waste gradually moves down the chamber in the opposite direction to the air flow. In the top section the waste dries at temperatures between 200 and 300°C. Further down the higher temperatures initiate the gasification reactions, producing syngas which is driven off and exits via an offtake at the top of the gasifier. At the base oxygen enriched air (approximately 36% O₂), produced by a Pressure Swing Adsorption (PSA) unit is fed into the gasifier. This reacts with the coke and remaining char from the waste feed

producing very high temperatures at the bottom of the vessel sufficient to melt the remaining ash and metals, the vast majority of organic matter having been converted to syngas by this point. The limestone also reacts in this region and helps to maintain a suitable composition for the production of a vitreous material which can be tapped off in molten form. The limestone also helps to reduce HCl emissions from the gasifier. An illustration of the gasifier and melting reactor is shown below.

Figure 2-14-3: Schematic representation of the slagging updraft gasifier



Source: Nippon Steel

Syngas passes from the gasifier to a combustion chamber via a cyclone separator where entrained dust and ash is removed and fed back into the base of the gasifier entrained with the oxygen-enriched air input. The syngas is then combusted with excess air in the combustion chamber producing high temperatures (approximately 1,100°C). The hot flue gases are then transferred through the boiler to raise steam.

The boiler produces superheated steam at 39.2 bar and 400°C, which passes through a turbine generator to produce electricity. The turbine is a condensing unit with a rated output of 23.5MW. Nippon Steel claim an electrical efficiency of 23%²⁹, but the use of coke to generate the high temperatures for melting makes it misleading to compare this plant to a conventional incinerator or starved-air gasifier as a proportion of the input feed is a high calorific value fossil fuel. In addition, the parasitic load of the plant is relatively high given the demand of the gasification process and oxygen enrichment plant.

A standard air pollution control system is installed to clean the flue gases to a sufficient level to meet the required emissions limits. The flue gases are first cooled via an economiser unit which recovers heat to pre-heat the boiler feedwater. A dry scrubber system is installed with lime injection to remove acid gases, with residues collected in a fabric filter. Finally, a Selective Catalytic Reduction (SCR) system uses ammonia injection in the presence of a catalyst to reduce NO_x emissions. The cleaned flue gases are then rejected via the stack.

The turbine has a rated electrical output of 23.5MW. The parasitic load of the plant is high relative to conventional incineration and gasification plants resulting in a reported electrical efficiency of 23% (gross).

²⁹ Dioxins Control And High-Efficiency Power Generation In A Large-Scale Gasification And Melting Facility, Nippon Steel, Date Unknown

The Nippon Steel Shin-Moji plant in Kitakyushu City, Fukuoka Prefecture is one of the largest waste gasification and ash melting plants in the world. The plant processes up to 216,000 tonnes per year of MSW and sludge. The plant has 3 lines each with a capacity of 240 tonnes per day, giving a total throughput capacity of 720 tonnes per day.

Figure 2-14-4: Photograph of the Shin-moji plant



Source: Nippon Steel

The Shin-Moji plant is required by the regulators to meet the emission limits to air as shown below.

Table 2-14-1: Local permit emission limit values for the Shin-Moji plant

| Pollutant | Permit limit values (mg/Nm ³) @ 12% O ₂ | Permit limit values (mg/Nm ³) @ 11% O ₂ |
|-----------------|---|---|
| Dust | 10 | 11.1 |
| CO | 37.5 | 41.6 |
| SO ₂ | 85.7 | 95.2 |
| HCl | 48.9 | 54.3 |
| NO _x | 98.2 | 109.1 |
| Dioxins/Furans | 0.08 ng/TEQ/Nm ³ | 0.1 ng/TEQ Nm ³ |

Source: WSP analysis of Nippon Steel data

The HCl and SO₂ limits are not as stringent as WID but the NO_x limit is half the WID value. The limits for dust, CO and dioxins/furans are similar.

The Shin-Moji plant achieves low total dioxin concentrations.

Table 2-14-2: Dioxin testing during early operation at Shin-Moji

| Output material | Unit | Value |
|---------------------|------------------------|-----------|
| Exhaust gas | ng-TEQ/Nm ³ | 0.0059 |
| Treated ash | ng-TEQ/g | 0.18 |
| Metal | ng-TEQ/g | 0.00096 |
| Slag | ng-TEQ/g | 0.0000015 |
| Effluent wastewater | ng-TEQ/L | 0.27 |
| Total emission | µg-TEQ/tonne of waste | 7.6 |

Source: Nippon Steel

Emissions to land are restricted to fly ash; all ash and metals from the melting process are collected and recycled. Reduction in the volume of waste going to landfill is the key driver for waste management in Japan where landfill void space is very limited, and the process ensures this is minimised as far as reasonably practicable. In total the volume of material sent to landfill is just 0.85% of the volume of the input waste.

Table 2-14-3: Solid outputs from the DMS plant at Shin-Moji

| Material | Mass (tonnes) | Mass fraction | Volume fraction |
|-----------------|---------------|---------------|-----------------|
| INPUT | | | |
| Municipal waste | 1509 | 100% | 100% |
| OUTPUTS | | | |
| Slag | 129 | 8.6% | |
| Metal | 20 | 1.4% | |
| Treated fly ash | 64 | 4.2% | 0.85% |

Source: Nippon Steel

The DMS plants are very reliable and Nippon Steel has developed an extensive database of operational data based from their 35 operating plants that have amassed thousands of operational hours. The areas of the process most prone to failure are the parts of the plant in close contact with the molten slag pool and Nippon Steel has used their extensive knowledge and experience from the steel industry to select materials and refractory that can withstand the challenging high temperature environment and erosive nature of the slag bath.

Annual availability is a difficult concept for Japanese engineering companies to grasp. In Europe EfW plants are designed and guaranteed to achieve typically 8,000 operational hours per year and the operators, once they have gained experience with the performance of their plant, will 'sweat the asset' and maximise the operational hours to 8,200 or 8,300 to increase revenues into the facility. The Japanese approach is to design the plant for the annual capacity required by the client; so for example, a client who requires a plant to process 200,000 tonnes per year will be sold a plant to process that quantity of waste in 300 days of operation, the remaining time in the year the plant will be shutdown for maintenance.

All Japanese slagging gasification processes produce a vitrified slag that is re-used in civil engineering and building applications. This subject is discussed in the Slag utilisation and re-use section, see page 173.

Nippon Steel is the world leader in the supply of slagging gasification facilities with 35 operational plants with two in South Korea supplied under licence by POSCO, the large Korean steel manufacturer. In summary, Nippon Steel has supplied 35 plants (72 lines) that are currently operating and processing approximately 2,483,100 tonnes per year. The company is constructing a further 5 plants (10 lines) that will process an additional 474,600 tonnes per year of waste.

Table 2-14-4: Nippon Steel DMS reference facilities

| Plant | Feedstock | Year | Capacity (tpd per line) | Number of lines | Annual capacity (tpa) |
|------------------------|------------------|------|-------------------------|-----------------|-----------------------|
| OPERATIONAL | | | | | |
| Kamaishi, Iwate | MSW | 1979 | 50 | 2 | 30,000 |
| Ibaraki, Osaka (1) | MSW | 1980 | 150 | 3 | 135,000 |
| Ibaraki, Osaka (2) | MSW | 1996 | 150 | 2 | 90,000 |
| Iryu, Hyogo | MSW | 1997 | 60 | 2 | 36,000 |
| EIFU, Kagawa | MSW | 1997 | 65 | 2 | 39,000 |
| Iizuka, Fukuoka | MSW | 1998 | 90 | 2 | 54,000 |
| Ibaraki, Osaka | MSW | 1999 | 150 | 1 | 45,000 |
| Itoshima, Fukuoka | MSW | 2000 | 100 | 2 | 60,000 |
| Kameyama, Mie | MSW | 2000 | 40 | 2 | 24,000 |
| Akita | MSW | 2002 | 200 | 2 | 120,000 |
| Maki, Niigata | MSW | 2002 | 60 | 2 | 36,000 |
| Kazusa, Chiba | MSW | 2002 | 100 | 2 | 60,000 |
| EIFU, Kagawa | MSW | 2002 | 65 | 1 | 19,500 |
| Takizawa, Iwate | MSW | 2002 | 50 | 2 | 30,000 |
| Narashino, Chiba | MSW | 2002 | 67 | 3 | 60,300 |
| Kochi West | MSW | 2002 | 70 | 2 | 42,000 |
| Tajimi City, Gifu | MSW | 2003 | 85 | 2 | 51,000 |
| Toyokawa, Aichi | MSW | 2003 | 65 | 2 | 39,000 |
| Oita City | MSW | 2003 | 129 | 3 | 116,100 |
| Munakata, Fukuoka | MSW | 2003 | 80 | 2 | 48,000 |
| Seinoh, Gifu | MSW | 2004 | 90 | 1 | 27,000 |
| Kita-kyushu, Fukuoka | Industrial waste | 2005 | 160 | 2 | 96,000 |
| Nippon Steel, Nagoya | ASR | 2006 | 120 | 1 | 36,000 |
| Shimada City, Shizuoka | MSW | 2006 | 74 | 2 | 44,400 |
| Kazusa, Chiba | MSW | 2006 | 125 | 2 | 75,000 |
| Kita-kyushu, Fukuoka | MSW | 2007 | 240 | 3 | 216,000 |
| Yangsan City, Korea | MSW | 2007 | 100 | 2 | 60,000 |
| Fukuroi, Shizuoka | MSW | 2008 | 66 | 2 | 39,600 |
| Narumi, Aichi | MSW | 2009 | 265 | 2 | 159,000 |
| Goyang City, Korea | MSW | 2009 | 150 | 2 | 90,000 |
| Shizuoka | MSW | 2010 | 250 | 2 | 150,000 |
| Himeji, Hyogo | MSW | 2010 | 134 | 3 | 120,600 |
| Matsue, Shimane | MSW+sludge | 2010 | 85 | 3 | 76,500 |

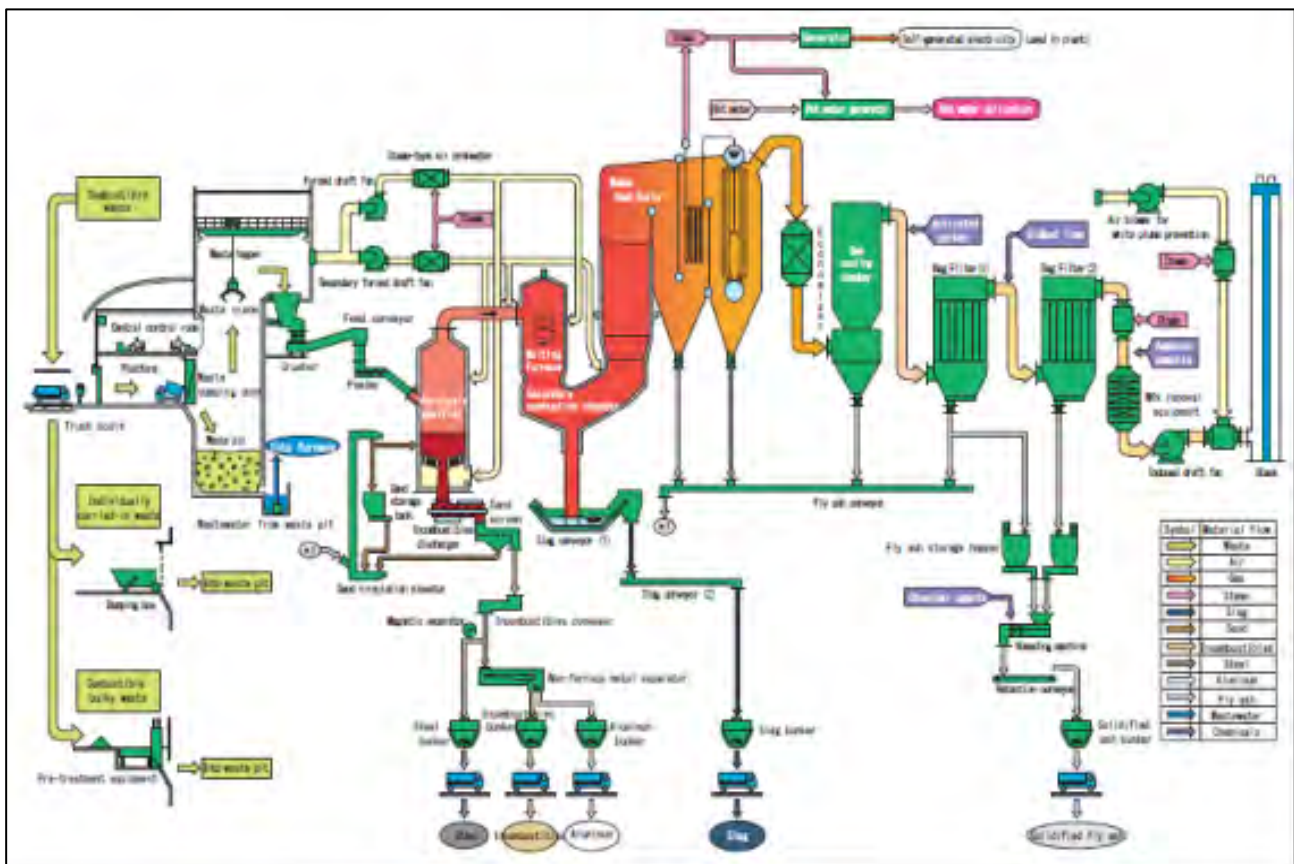
| Plant | Feedstock | Year | Capacity (tpd per line) | Number of lines | Annual capacity (tpa) |
|---------------------------|----------------|------|-------------------------|-----------------|-----------------------|
| Okazaki, Aichi | MSW+ash+sludge | 2011 | 190 | 2 | 114,000 |
| ISCEU, Iwate | MSW | 2011 | 73.5 | 2 | 44,100 |
| UNDER CONSTRUCTION | | | | | |
| Akita City | MSW+ash+sludge | 2012 | 230 | 2 | 138,000 |
| Sakai, Osaka | MSW | 2013 | 225 | 2 | 135,000 |
| Saitama City | MSW+ash+sludge | 2015 | 190 | 2 | 114,000 |
| Tobashisei, Mie | MSW | 2014 | 47.5 | 2 | 28,500 |
| Komaki, Aichi | MSW | 2015 | 98.5 | 2 | 59,100 |

Source: WSP analysis of Nippon Steel data

Kobelco

Kobelco developed their gasification/melting system from two technologies already in their portfolio; fluidised bed combustion and high temperature melting furnace. They combined the two and added a waste heat recovery boiler and flue gas cleaning back-end.

Figure 2-14-5: Flow schematic of the Kobelco gasification/melting process



Source: Kobelco

The fluidised bed gasifier offers a degree of flexibility and robustness with respect to waste composition and CV variability. The process can also accommodate wastes with higher ash content. If the CV of the waste is low, such as for MSW then the fluidising air is pre-heated with steam from the boiler in a heat exchanger. For applications with RDF where the CV is much higher then this facility is not necessary.

The produced syngas flows into the secondary melting furnace where it is combusted at high temperature and melts the dust carried over with the syngas to produce a molten slag which flows from the base of the secondary combustor into a water bath slag cooler and granulator.

The boiler is not conventional because the heat recovery heat transfer surface buried into the refractory of the high temperature melting furnace is integrated into the boiler as an additional evaporation stage. Steam is converted to electricity via a conventional steam turbine/generator.

The flue gas exits the economiser and passes through a gas cooling tower (quench) to be pre-conditioned before it enters the dry scrubbing system where sodium bicarbonate and activated carbon are injected to remove acid gases and pollutants such as dioxins/furans and volatile heavy metals such as mercury before the

flue gas enters the baghouse to remove the dust. Finally the flue gas flows through a SCR³⁰ reactor to remove NOx and then passes up the stack to atmosphere.

The contaminated fly ash from the boiler and gas cleaning part of the process is treated with heavy metal chelating agents and is solidified prior to the safe disposal.

The re-use of the vitrified slag product is discussed in Slag utilisation and re-use, see page 173.

The largest plant supplied by Kobelco is the Sagamihara facility in Kanagawa Prefecture near Tokyo. The plant processes 525 tonnes per day in three lines, which is about 160,000 tonnes per year. The plant produces 10 MW of electricity and has a land take of 47 hectares.

Figure 2-14-6: The Sagamihara slagging gasification plant



Source: Kobelco

Table 2-14-5: Kobelco slagging gasification reference facilities

| Plant | Feedstock | Year | Capacity (tpd per line) | Number of lines | Annual capacity (tpa) |
|--------------------|-----------|------|-------------------------|-----------------|-----------------------|
| OPERATIONAL | | | | | |
| Chubu Kamikita | MSW | 2000 | 30 | 2 | 18,000 |
| Hiroshima | MSW | 2002 | 65 | 2 | 39,000 |
| Kazuno, Akita | MSW | 2002 | 30 | 2 | 18,000 |
| Ishinomaki | MSW | 2002 | 115 | 2 | 69,000 |

³⁰ Selective Catalytic Reduction

| Plant | Feedstock | Year | Capacity (tpd per line) | Number of lines | Annual capacity (tpa) |
|---------------------------|-----------|------|-------------------------|-----------------|-----------------------|
| Nakatsugawa, Gifu | MSW | 2004 | 49 | 2 | 29,400 |
| Ono-Katsuyama, Fukui | MSW | 2006 | 42 | 2 | 25,200 |
| Nemuro, Hokkaido | MSW | 2007 | 31 | 2 | 18,600 |
| Sashima, Ibaraki | MSW | 2008 | 103 | 2 | 61,800 |
| Iwade | MSW | 2008 | 30 | 2 | 18,000 |
| Pangyo, Korea | MSW | 2009 | 45 | 2 | 27,000 |
| Sagamihara | MSW | 2010 | 175 | 3 | 157,500 |
| Kawagoe | MSW | 2010 | 132.5 | 2 | 79,500 |
| Paju Unjeong, Korea | MSW | 2011 | 45 | 2 | 18,000 |
| UNDER CONSTRUCTION | | | | | |
| Nishiakigawa, Tokyo | MSW | 2014 | 58.5 | 2 | 35,100 |
| Haga, Tochigi | MSW | 2014 | 71.5 | 2 | 42,900 |

Source: WSP analysis of Kobelco data

Kobelco has installed 13 slagging gasification plants (27 lines) that are currently operating and processing 588,000 tonnes per annum of MSW. Two further plants (4 lines) are under construction and will process an additional 39,000 tonnes per year of MSW from 2014.

JFE

JFE was formed from the merger of Kawasaki Steel and NKK. Both companies had been active in the development and licensing of gasification technologies for waste treatment. Kawasaki Steel had licensed the Thermoselect process and NKK had developed an updraft shaft gasification reactor (cf. Nippon Steel).

JFE constructed seven Thermoselect plants but have stated that they no longer offer the technology as it is too expensive. The Table below shows they have ten operational plants and a further development in the design stage. Interestingly, three of the plants are processing material mined from existing landfills, which is an interesting proposition in Japan as landfill void space is an extremely valuable asset.

Table 2-14-6: JFE slagging gasification reference facilities

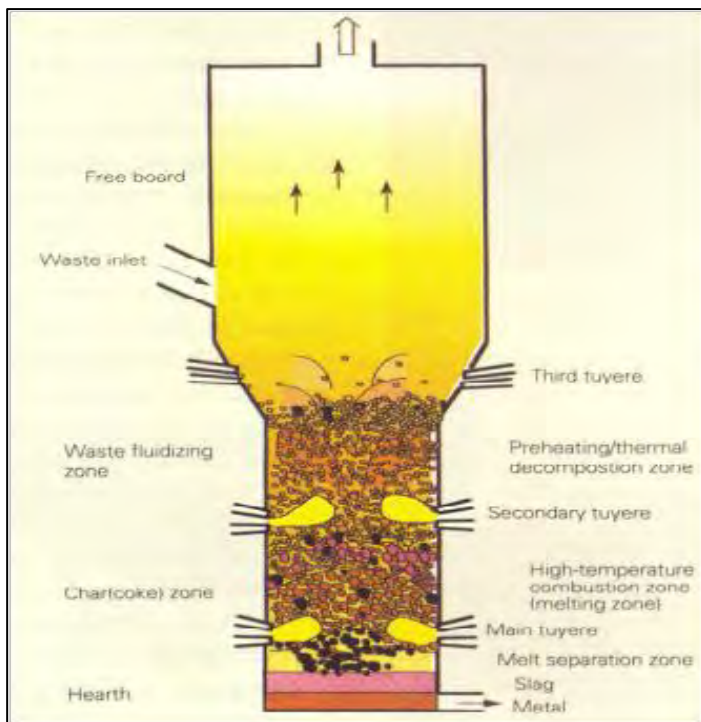
| Plant | Feedstock | Year | Capacity (tpd per line) | Number of lines | Annual capacity (tpa) |
|---------------------------|----------------------------|------|-------------------------|-----------------|-----------------------|
| OPERATIONAL | | | | | |
| Kamamigahara, Gifu | MSW | 2003 | 64 | 3 | 57,600 |
| Hidaka Chubu, Hokkaido | MSW | 2003 | 19 | 2 | 11,400 |
| Amagi, Fukuoka | MSW | 2003 | 60 | 2 | 36,000 |
| Saiki, Ohita | MSW, landfill minings | 2003 | 55 | 2 | 33,000 |
| Morioka Shiwa, Iwate | MSW, landfill minings | 2003 | 80 | 2 | 48,000 |
| Fukuyama, Hiroshima | RDF | 2004 | 314 | 1 | 94,200 |
| Kasama, Ibaraki | MSW, industrial waste, IBA | 2005 | 72.5 | 2 | 43,500 |
| Aki, Kochi | MSW, landfill minings | 2006 | 40 | 2 | 24,000 |
| Hamada, Shimane | MSW | 2006 | 49 | 2 | 29,400 |
| Chikushino, Fukuoka | MSW | 2008 | 125 | 2 | 75,000 |
| UNDER CONSTRUCTION | | | | | |
| Albano, Italy | RDF | 2013 | 308 | 2 | 184,800 |

Source: WSP analysis of JFE data

The company developed a waste melting technology utilising their experience in gasification. The origins of the process, known as Gasification Melting Furnace, can be found in NKK's expertise in fluidised bed combustion and blast furnace technology. Waste is gasified at a temperature in excess of 1000°C and melted in one step in a shaft furnace (cf. Nippon Steel), which maintains the upper layer in a molten state. Molten metal and slag are removed from the base at separate tapping points. The syngas is de-dusted then passes through a waste heat boiler and gas cleaning system which includes a combination of dry and wet scrubbing. It is then combusted in a gas turbine to generate electricity.

The process was designed to meet the local Japanese market's interest in waste melting techniques as alternatives to incineration for disposal of municipal waste.

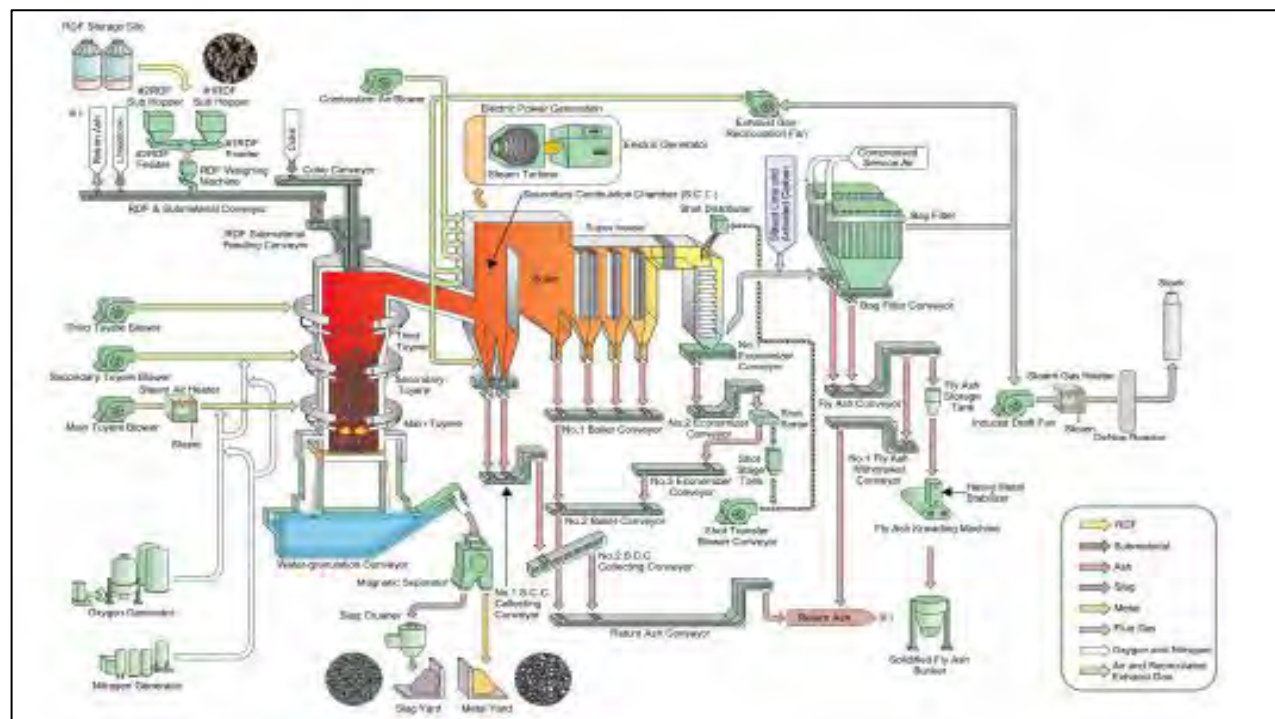
Figure 2-14-7: Updraft shaft reactor (JFE design)



Source: JFE

The 'flagship' plant is the single line plant at Fukuyama, near Hiroshima. The plant process 314 tonne per day of pelletised RDF, produced by seven plants within the city, in a single line (13 tonnes per hour). The boiler produces steam at 60 bar and 450°C and exports 20 MWe from the steam turbine/generator. The flue gas is cleaned using a dry scrubbing system (lime + activated carbon) and a de-NOx process (SNCR).

Figure 2-14-8: Process schematic of the Fukuyama waste melting plant



Source: JFE

The plant produces melted slag (9.9% of input) and metal (0.6% of input), which are recycled. We understand the slag has passed the necessary rigorous leach testing protocol required by the Japanese regulators.

JFE report the overall electrical conversion efficiency of the process is approximately 30%.

JFE has supplied some emission data to air which is shown below:

Table 2-14-7: Air emission data from the Fukuyama plant

| Pollutant | Regulatory value (mg/Nm ³) | Measured value (mg/Nm ³) |
|---|--|--------------------------------------|
| Dust | < 11.1 | 1.1 |
| SO ₂ | < 63.4 | 3.1 |
| NOx | < 114.0 | 84.3 |
| CO | < 41.6 | 4.1 |
| Dioxins/Furans (ng/Nm ³ I-TEQ) | < 0.06 | 0.000059 |
| all data normalised to 11% O ₂ , dry basis | | |

Source: JFE

Figure 2-14-9: The Fukuyama Waste melting Plant



Source: JFE

Hitachi Zosen

Hitachi Zosen is another large engineering company in Japan that has built many waste combustion plants based on both moving grate and fluidised bed designs. The company has developed a slagging gasification process based on their fluidised bed combustion system and built eight plants in Japan, as shown below.

Table 2-14-7: Hitachi Zosen slagging gasification reference facilities

| Plant | Feedstock | Year | Capacity (tpd per line) | Number of lines | Annual capacity (tpa) |
|---------------------------|-----------|------|-------------------------|-----------------|-----------------------|
| OPERATIONAL | | | | | |
| Sakurai, Nara | MSW | 2002 | 75 | 2 | 45,000 |
| Nagasaki | MSW | 2002 | 29 | 2 | 17,400 |
| Ishikawa Hokubu | MSW | 2003 | 80 | 2 | 48,000 |
| Takamatsu, Kagawa | MSW | 2004 | 100 | 3 | 90,000 |
| Ariake, Kumamoto | MSW | 2006 | 25 | 2 | 15,000 |
| Toyota, Aichi | MSW | 2007 | 135 | 3 | 121,500 |
| Sano, Tochigi | MSW | 2007 | 128 | 1 | 38,400 |
| Kimotsuki, Kagoshima | MSW | 2008 | 64 | 2 | 38,400 |
| UNDER CONSTRUCTION | | | | | |
| Namyangju, Korea | MSW | 2013 | 52 | 1 | 15,600 |

Source: WSP analysis of Hitachi Zosen data

The process is similar to the Kobelco process discussed above.

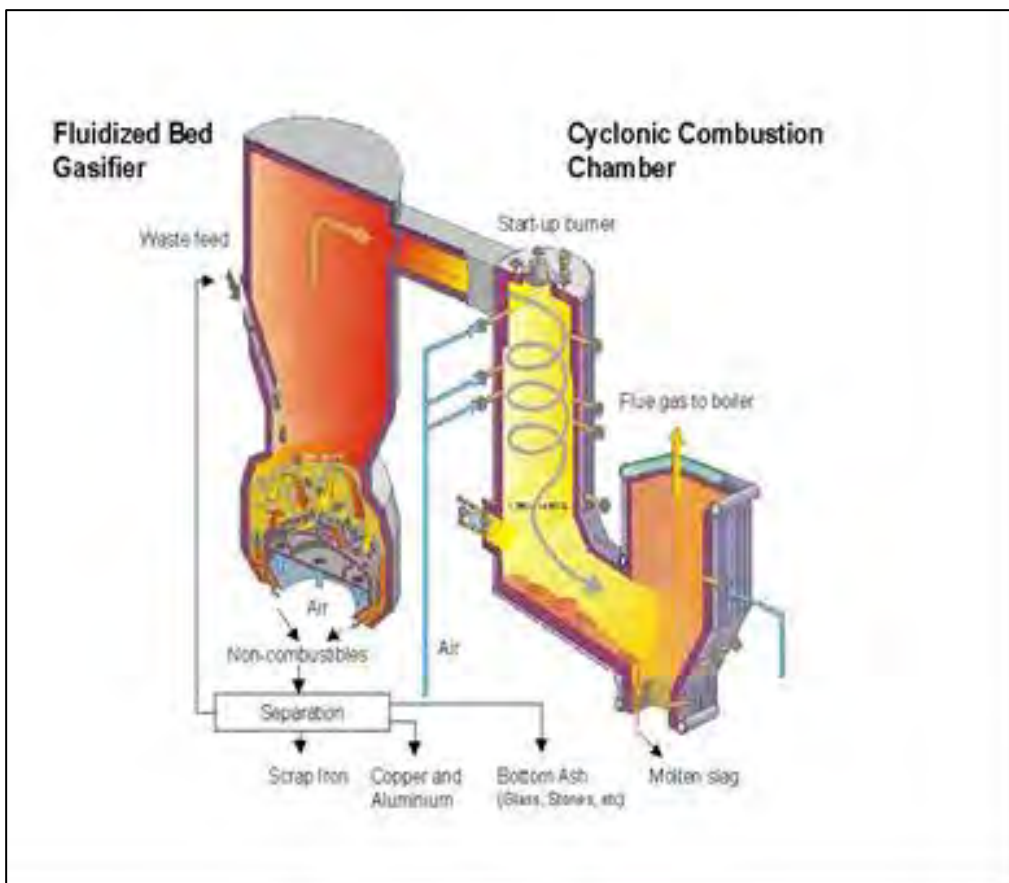
Ebara

The “Twin Internally revolving Fluidized bed Gasifier” process (TIFG) was developed by Ebara Corporation (Ebara) in Japan as part of the Japanese national development strategy to make high efficiency, sustainable waste disposal technologies available in Japan. Ebara has modified the design of their well proven fluidised bed incineration (TIF) technology to operate in a gasification mode. They have combined this with another well proven technology for ash melting (Meltex) to produce a new concept for waste disposal. This technology has been officially approved by the Japanese Authorities and a number of commercial plants have been built or are under construction in Japan.

An inclined distributor plate is used with a number of separate fluidising air supply chambers to provide differential air flows across the bed. In addition to promoting rapid and turbulent mixing of waste and bed material through the revolving action, heavy inert non-combustibles migrate to the sides of the bed for removal. An angled furnace wall configuration immediately above the fluidised bed zone encourages the revolving action, restrains bed expansion and minimises bed carry-over. The controlled elliptical circulation patterns converge in the centre of the bed ensuring effective vertical and lateral mixing which in turn produces high combustion efficiency.

The design has been modified so that the waste is gasified within the fluidised bed. Sufficient air is injected from below to provide the fluidising action, but the volume is kept well below the stoichiometric amount required to combust the organic materials. The gasifier is operated at 500 - 600°C (cf: conventional incineration which operates at temperatures between 850 - 900°C).

Figure 2-14-10: Schematic of the Ebara TIFG process



Source: Ebara

Shredded waste is fed into the hot revolving mass of bed material, typically silica sand, and the organic compounds are transferred to the gas phase. Larger non-combustible components of the waste, such as metallic waste, glass and stones, are not oxidised or sintered but pass out of the base of the fluidised bed and

are recovered as bed ash. The metal fractions can then be separated by magnetic and eddy-current means into ferrous and non-ferrous fractions for recycling.

The produced syngas and entrained particulates (both carbonaceous and inorganic ash particles) pass out of the freeboard zone of the fluidised bed and over into a cyclonic combustion chamber. In this, the syngas and entrained carbonaceous material are combusted at temperatures between 1350 and 1450°C by the addition of secondary air. The high temperature environment in the cyclonic furnace is sufficient to melt the inorganic ash components to produce a molten slag which is removed from the process via a water quench to produce a granulate - which is claimed to meet all common leachability regulations.

Since the fluidised bed is operated in gasification mode then the flue gas mass flow produced is smaller than in a conventional incinerator which allows the use of a compact sized steam boiler and air pollution control train. The energy content of the waste is converted via the steam cycle into electricity and/or heat energy.

Table 2-14-8: Ebara slagging gasification reference facilities

| Plant | Feedstock | Year | Capacity (tpd per line) | Number of lines | Annual capacity (tpa) |
|---------------------|---------------------|------|-------------------------|-----------------|-----------------------|
| OPERATIONAL | | | | | |
| Aomori | ASR + sewage sludge | 2001 | 225 | 2 | 135,000 |
| Toyama | ASR + plastics | 2001 | 63 | 1 | 18,900 |
| Sakata | MSW | 2002 | 98 | 2 | 58,800 |
| Kawaguchi | MSW | 2002 | 140 | 3 | 126,000 |
| Ube | MSW | 2002 | 66 | 3 | 59,400 |
| Chuno | MSW | 2003 | 56 | 3 | 50,400 |
| Minami-Shinshu | MSW | 2003 | 46.5 | 2 | 27,900 |
| Nagareyama | MSW | 2004 | 69 | 3 | 62,100 |
| Tokyo Rinkai Corp. | Industrial waste | 2006 | 275 | 2 | 165,000 |
| Shiga | MSW | 2007 | 60 | 3 | 54,000 |
| Taegu City, Korea | MSW | 2008 | 70 | 1 | 21,000 |
| Eunpyeong, Korea | MSW | 2009 | 48 | 1 | 14,400 |
| Hwasung City, Korea | MSW | 2010 | 150 | 2 | 90,000 |
| Okinawa | MSW | 2010 | 103 | 3 | 92,700 |
| Gimpo, Korea | MSW | 2012 | 42 | 2 | 25,200 |

Source: WSP analysis of Ebara data

Data for emissions to air is from 2003 and is averaged across a two month time period:

Table 2-14-9: Emissions to air from the Toyohashi plant

| Pollutant | Unit of measurement | Regulatory limit | Actual measured data |
|---|--------------------------|------------------|----------------------|
| Dust | mg/Nm ³ | < 10 | < 1 |
| SO ₂ | mg/Nm ³ | < 28.6 | < 2.9 |
| HCl | mg/Nm ³ | < 16.3 | < 1.6 |
| NO _x | mg/Nm ³ | < 98.2 | 29.7 |
| CO | mg/Nm ³ | < 12.5 | 2.5 |
| Dioxins/Furans | ng/Nm ³ I-TEQ | < 0.05 | 0.0073 |
| Based on flue gas with 12% O ₂ , dry basis | | | |

Source: Ebara

Figure 2-14-11: The Kawaguchi plant



Source: Ebara

Mitsui Engineering & Shipbuilding (MES)

MES licensed the technology from Siemens who developed the process and built a plant at Fürth in Germany. This plant experienced some significant technical issues and ultimately it was shutdown and removed from the site and Siemens withdrew from offering the technology. MES has subsequently modified parts of the process and constructed eight plants that are operating satisfactorily.

Table 2-14-10: Mitsui Engineering & Shipbuilding slagging gasification reference facilities

| Plant | Feedstock | Year | Capacity (tpd per line) | Number of lines | Annual capacity (tpa) |
|-----------------------|-----------|------|-------------------------|-----------------|-----------------------|
| OPERATIONAL | | | | | |
| Yame Seibu, Fukuoka | MSW | 2000 | 110 | 2 | 66,000 |
| Toyohashi | MSW | 2002 | 200 | 2 | 120,000 |
| Ebetsu, Hokkaido | MSW | 2002 | 70 | 2 | 42,000 |
| Kyohoku, Yamanashi | MSW | 2003 | 80 | 2 | 48,000 |
| Genkai, Fukuoka | MSW | 2003 | 130 | 2 | 78,000 |
| Nishi-iburi, Hokkaido | MSW | 2003 | 105 | 2 | 63,000 |
| Hamamatsu, Shizuoka | MSW | 2009 | 150 | 3 | 135,000 |
| Yangju City, Korea | MSW | 2009 | 100 | 2 | 60,000 |

Source: WSP analysis of Mitsui data

The process combines pyrolysis with high temperature combustion. Following pre-treatment of the solid waste to remove recyclable material and reduce the size of the solid feedstock to less than 200 mm, the waste is fed via a screw conveyor to the thermal conversion drum.

Many of the problems during commissioning at Fürth related to this material feeding method when utilising a variable waste feedstock.

The drum is heated in an oxygen deficient atmosphere to a temperature of 450°C and retained for a residence time of approximately one hour. The conversion drum axis is tilted 1.5 degrees from the horizontal and rotates at approximately 3 rpm.

Internal heating tubes transfer heat to the material that is to be converted which is thoroughly mixed in the pyrolysis stage. The syngas produced is supplied directly to the second stage combustion chamber. Solid residues are removed, cooled to less than 150°C and screened to separate fine and coarse recyclable fractions. The coarse fraction chiefly comprises ferrous and non-ferrous metals and inert material. The char, which contains 99% of the solid carbon formed in the pyrolysis process, is mixed with recycled dust fractions from the boiler and flue gas cleaning processes. This dust mixture has an approximate carbon concentration of 30% resulting in a minimum heating value of around 10 MJ/kg.

The syngas and char/dust are burned at approximately 1300°C in the combustion chamber. The combustion temperature is 100 to 150°C above the fusion point of ash compounds, consequently, the un-recyclable ash residues which are injected into the high temperature combustion chamber are converted into a molten slag which flows downwards into the wet slag removal unit. The slag granulates to form a vitreous substance that can be utilised, as a road construction material for example, without further treatment. The temperature, residence time and turbulence in the combustion stage ensure that all organic compounds are destroyed. High burn out and low NO_x formation are ensured by uniform temperature distribution affected by flue gas recirculation. Siemens guaranteed the percentage of unburned carbon in the granulated slag for the Fürth plant at <0.1%. The results obtained at Fürth during commissioning indicated a value of less than 0.01% - which is similar to the original test results claimed for the Ulm and Yokohama pilot plants.

The thermal energy contained in the resulting flue gases is used to generate steam in a heat recovery boiler (400°C and 40 bar) which is then used to generate electricity and/or heat. The flue gases are cooled to around 250°C before passing to the flue gas cleaning/by-product recovery section of the plant.

The flue gas is scrubbed to meet the requirements of relevant air emission legislation. Additionally, recovery processes for gypsum, HCl and heavy metals may be applied depending on the requirements of the application. Boiler ash, fly ash and spent active carbon from the bag filter are fed back to the melting furnace and the residues requiring ultimate disposal are salts and sludge from the waste water treatment plant.

Data for emissions to air is from 2002 and is averaged across a five month time period:

Table 2-14-11: Emissions to air from the Toyohashi plant

| Pollutant | Unit of measurement | Regulatory limit | Actual measured data |
|---|--------------------------|------------------|----------------------|
| Dust | mg/Nm ³ | < 20 | < 1 |
| SO ₂ | mg/Nm ³ | < 71.4 | 56.2 |
| HCl | mg/Nm ³ | < 65 | 35.8 |
| NOx | mg/Nm ³ | < 98.2 | 45.9 |
| Dioxins/Furans | ng/Nm ³ I-TEQ | < 0.01 | 0.0032 |
| Based on flue gas with 12% O ₂ , dry basis | | | |

Source: MES

Figure 2-14-12: Pyrolysis reactor at Toyohashi



Source: MES

Figure 2-14-13: Toyohashi plant

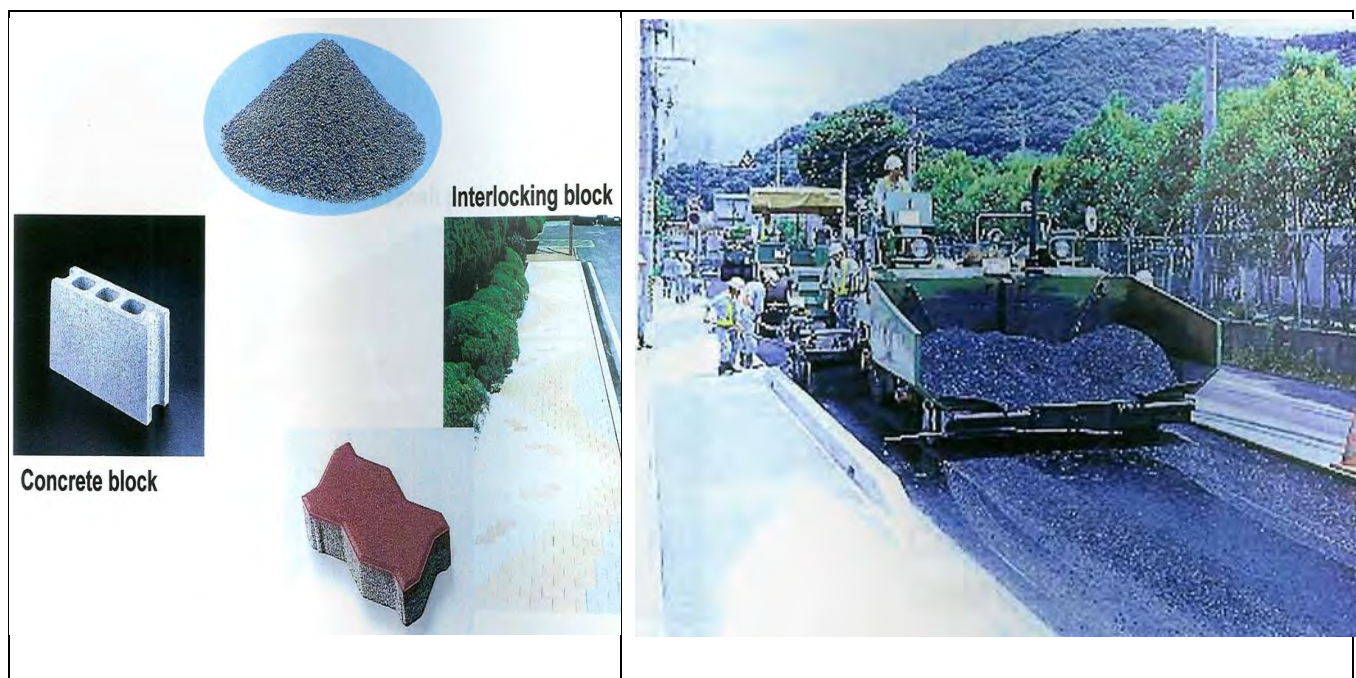


Source: MES

Slag utilisation and re-use

The slagging of the inorganic content of the waste to produce a vitrified slag material has enabled the production of a re-usable material for civil engineering applications and metallurgical processing. The slag is converted into products such as paving slabs, roof tiles, etc which have passed the relevant Japanese regulatory tests to be accepted as building products, as shown in the following table:

Figure 2-14-14: Re-usable products from the vitrified slag and metals recovered from the DMS process



Source: Nippon Steel

WSP has been provided with batch test leaching data for slag produced at one of the operating plants from five of the leading suppliers of slagging gasification technologies in Japan. The data sets provided by Kobelco, Nippon Steel, JFE, Ebara and Mitsui are based on the Japanese Ministry of Environment Notification No. 46³¹ (JLT-46) leaching test.

The data presented for a selection of heavy metals (Hg, Cd, Pb, Cr⁶⁺, As, Se) indicates that the slag passes the Regulation leaching test (JLT-46) easily for all metals. This is not an unexpected result because the slag produced by all of these processes is a vitrified product and although the slag sample is ground to <2mm in size, the mild pH employed by the test procedure should not affect the glass/silicate matrix but would only dissolve metal species from the external surfaces of the particles.

³¹ Environment Protection Law No. 46: Environment Protection Standards for Soil Contamination. Ministry of the Environment Notification No. 46 (August 23, 1991)

Table 2-14-12: Comparison of slag leaching data from the leading gasification plant suppliers in Japan

| Heavy metal | MOE Notification No. 46 | Kobelco | Nippon Steel | JFE | Ebara | Mitsui |
|--------------------------------|-------------------------|---------|--------------|---------|---------|---------|
| As | 0.01 | <0.001 | <0.005 | <0.005 | <0.001 | <0.001 |
| Cd | 0.01 | <0.001 | <0.001 | <0.005 | <0.001 | <0.001 |
| Cr ⁶⁺ | 0.05 | <0.005 | <0.005 | <0.04 | <0.005 | <0.01 |
| Pb | 0.01 | 0.001 | <0.005 | <0.005 | <0.005 | 0.002 |
| Hg | 0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 |
| Se | 0.01 | <0.001 | <0.005 | <0.005 | <0.001 | <0.002 |
| All concentration data is mg/l | | | | | | |

Source: Various

The vitrified slag has been utilised in Japan in several construction applications (see photographs below):

- as a replacement aggregate;
- mixed with asphalt for road and car park surfacing;
- manufacture of roof tiles;
- manufacture of paving slabs;
- manufacture of concrete blocks.

Case Study 15 – Current Status of Plasma Gasification

Preamble

Although plasma gasification is hailed as the next technology to solve the conversion of waste to electricity without the need to employ incineration technologies there are no large scale plants using this technology in operation. We have chosen to produce a summary of the current status of the plasma gasification of waste but have included descriptions of processes that WSP considers the nearest to commercial operation and not all processes that are currently being promoted.

Overview

Plasma processes are attracting more interest than ever. Municipalities in Europe, North America and Asia are considering facilities at scales of up to 1 million tonnes per annum; orders and projects have been announced for processing clinical waste; tyres; hazardous wastes, including spent munitions; shipboard waste on naval vessels and cruise liners; and melting incinerator ashes to produce, in some countries, a product for recycling into construction applications. Political decision makers are attracted to plasma because they see it as a modern, high technology solution. Corporates, large and small, sense a significant business opportunity.

Yet, more traditional voices from within the waste management sector say that using plasma for large-scale processing of conventional wastes is unproven, of doubtful economics and that, because of this limited track record, unbankable. Such longstanding arguments must now be reviewed in the context that a few new demonstration projects involving municipal solid wastes are operating and large-scale commercial projects have been announced and some currently being built. Indeed the climate in which new technologies are at present being considered have changed: the GHG impact of waste treatment is more heavily under scrutiny; oil prices are extremely volatile having reached \$140+/barrel on June 27th 2008; there have been significant developments to better exploit the resource value of waste via more efficient energy recovery and a move to transport fuels and pipeline quality gas. However, the current economic climate makes it much more difficult for technologies, considered to be novel or innovative, to secure bank finance.

Unfortunately, there are no commercially operating plasma gasification plants that could be considered state-of-the-art and therefore we are providing a review of the current status of plasma gasification, which will allow the reader to understand where the technology sits within the panoply of WtE technologies.

A general discussion of plasma gasification processes is included in Overview of Thermal Treatment Technologies, page 8 and therefore here we discuss who the leading promoters of this technology type are and the current status of their development of the process they are offering to the marketplace and of any projects constructed or planned.

The advantages of plasma processes derive partly from the underlying technology and partly from the market's perception of such concepts. Key plus points include:

- an ability to process a wider range of inputs than most other technologies;
- can be practical at smaller scales than many other competitive approaches;
- a number of variants are available, from which a specific configuration can be chosen to meet particular requirements for specific projects;
- solid residues are vitreous, not ash, making re-use or disposal less challenging;
- seen as more sophisticated, and hence better, than conventional incineration by political decision makers;
- the high temperatures within the plasma are assumed by the market to result in more complete destruction of waste than processes operating at lower temperature, which leads to a perception that such systems

pose less risk to human health and have a better environmental performance; which may ease public acceptance of this approach.

- the view that the high operating temperatures can facilitate a clean syngas product, which is essential for further exploiting the resource value of MSW via greater efficiency energy recovery (employing gas engines, gas turbines or fuel cells) or the production of chemicals as alternative road transportation fuels.

Like many technologies that are now being promoted for waste applications, plasma technologies are not new, having been applied successfully in the metallurgical, chemical and space exploration industries for many years. Their use as a heat source in metallurgical furnaces has been well documented and plasma-based deposition technologies are a standard method of applying thin-layer coatings to a range of substrates including glass and ceramics for military and commercial applications. What is relatively new is that some developers of plasma processes are targeting commercial scale waste applications for an increasingly broad range of wastes, with a view to capitalising on potential business opportunities that have arisen in many countries.

There are some 50 active technology providers in this sector, so potential customers have a wide array of options available; but most of these companies have not yet completed a full-scale commercial project.

Plants have so far been at small scale. Only recently have some companies begun to establish a track record for treating certain types of hazardous and industrial wastes, predominantly in the USA and Japan. In the latter country, several technologies are becoming commercially proven for vitrifying incinerator ashes, but plasma is relatively unproven anywhere in the world for treating household and non-hazardous commercial/industrial wastes at a relevant scale: there are only two plants, both in Japan, treating these types of wastes on a commercial basis.

An attraction to this technology is that systems are available to treat wastes with a broad range of calorific values, particularly low calorific value inorganic wastes or liquid wastes with high water content that would not normally be suitable for processing by other standard types of thermal technology.

The main solid output from plasma processes is vitrified slag, which can be recycled where markets are available. Molten metal can also be recovered from some processes where there are sufficient volatile metals in the waste input³². Some processes can be designed to produce an almost completely oxidised gas with low levels of pollutants, while other process designs allow the production of a syngas, which can be combusted to produce energy or might also be used as a chemical feedstock. Therefore plasma technologies offer significant flexibility and it is possible to configure systems to maximise resource recovery.

Plasma processes have historically been regarded as overly complex, costly and difficult to implement. Issues such as electrode lifetime and the high energy requirement have been seen as major hurdles to the commercialisation of the technology for large scale applications. As we will see in this report, there are grounds for cautious optimism – as the results of development and pilot scale projects begin to emerge, evidence is being generated that, for some types of projects, such issues may not be ‘stoppers’ to the adoption of this technology. Yet, if the evidence were compelling, one would expect to see more of it being put into the public domain by the process developers – instead some impose confidentiality constraints before releasing very limited evidence which is not often as clear-cut as has been implied.

Plasma is seen by some as a sophisticated technology that offers the prospect of complete destruction of waste without the environmental disadvantages that are associated with incineration because the creation of plasma involves very high temperatures. But, in many designs, this high temperature is not sustained in the zones within which waste conversion takes place, so this perception is not justified.

Plasma Gasification

There are two generic configurations of plasma gasification: configurations in which the plasma generator (i.e. the plasma torch or electrodes) is contained within the main waste conversion reactor; and those in which the plasma generator is external to the main waste conversion reactor and is used as a source of hot gases. The latter has often been referred to as ‘plasma assisted gasification’.

³² The molten slag and the molten metal can be easily separated due to their density difference.

Plasma gasification is carried out under oxygen depleted conditions, which results in the production of syngas, a vitrified slag and molten metal, the proportions and composition of which will depend on the composition of the input waste. The main driver in the development of this type of process is the opportunity to recover gases rich in chemical energy that can be utilised in high efficiency energy recovery systems or used as a chemical feedstock. Also, because the process involves less air and can result in lower volumes of off-gases, it is seen by many developers as suitable for applications in which space is at a premium (e.g. onboard ships). The smaller flue gas volumes also bring benefits in terms of the scale of downstream air pollution control equipment; though this does not necessarily translate into a reduced complexity or lower cost. Emissions of pollutants such as nitrogen oxides (NO_x) and sulphur dioxide (SO₂) are avoided, but other reducing contaminants such as H₂S (hydrogen sulphide), NH₃ (ammonia) and COS (carbonyl sulphide) may have to be abated. Some trace contaminants can require more sophisticated and potentially more expensive counter-measures than would be necessary with either plasma combustion or conventional incineration.

In the context of this report a very important question is – “are plasma processes suitable for processing large volumes of MSW?”

Driven by the size of the commercial opportunity some plasma process developers are anxious to compete directly with incineration for mass processing of municipal solid waste. Below we discuss six key challenges associated with such applications:

- heat transfer;
- scale and modularity;
- heterogeneity;
- relatively low calorific value;
- relatively high moisture content (c. 30 - 60% wt);
- high ash content.

Heat transfer: As the plasma arc is a relatively localised source of heat generation, distributing the high temperatures through larger volumes of waste may be a significant challenge for large scale reactors. Systems currently being used commercially are of small capacity, and therefore scale-up for treating larger volumes of waste (with the associated greater heat transfer needs) involves a potentially significant technical risk. Some process developers have designed systems that utilise more than one plasma torch (and more than two electrodes) so that the heat is better distributed through large waste conversion vessels, but so far none of these systems have been implemented commercially at a scale that would be relevant to competing with large scale municipal waste incinerators.

Scale and modularity: Arguably, processes can be configured to be modular. But the need for multiple torches and multiple refractory lined reactors could be a high cost barrier to highly modular approaches. Moreover the technology is yet to be proven at a reasonable scale to make modular implementation a strategic alternative³³. While plasma processes have been proposed for treating large volumes of waste, the largest commercial waste processing plant in operation of which we are aware has a design capacity of 166 Tpd (c. 50,000 Tpa). In this context the nervousness shown by many municipalities and investors alike in considering plasma for larger scale applications is understandable.

Waste heterogeneity: The heterogeneous nature of MSW is potentially a problem for plasma processes. Variations in the type and composition of waste, as well as the size and feeding characteristics of the input material, could all affect the process operability and therefore may influence its design. Commercial experience with plasma processes has shown that they can process materials of various sizes, even large sealed drums. But operation has so far been mainly on a batch basis, where heat transfer rates and residence time are not as critical as in the continuous operation that would be required for processing large volumes of MSW.

The size of the input waste particles is significant: the smaller the size, the higher the heat transfer rate. Heat transfer rates determine the degree of volatilisation of the solid waste and hence the composition of the gases

³³ Proposals for large scale plants have planned up to 10 reactors in parallel. The proponent's economic modelling seems to indicate that such an approach is economically feasible, though this has yet to be confirmed through a commercially demonstrated Case Study.

evolved from waste degradation - the lower the heating rate, the higher the risk of tars and particulates being carried out of the plasma reactor. Minimising tar and particulate carryover are not insurmountable challenges provided that the process design incorporates suitable measures to minimise their formation or provides downstream equipment to abate these contaminants, though this may have cost implications.

Experience with non-plasma pyrolysis and gasification projects has shown that tar and particulate carry-over can be a significant and costly problem, particularly when the process is designed to recover a syngas for use as a chemical feedstock or an energy carrier. As the types of plasma systems being promoted for MSW applications use gasification, third parties must assume that treating large volumes of waste such as MSW, implies significant technical risk until sufficient data is obtained from suitably scaled projects.

Calorific Value: We have already indicated that low CV waste is not a problem for plasma processes. However, this does not mean that there will be no limit on the range of calorific values that can be processed within an individual facility. Temperature limitations of the plasma reactor and the capabilities of downstream equipment are two factors that will have to be considered in determining the inputs that can be processed at a particular facility.

Moreover, the lower the CV the less energy will be produced per tonne of input, which will directly impact on plant economics. The trend over the last few years in many countries has been increasing waste CV. Gasification processes (including plasma gasification) generally are very well suited to accommodating waste input with a higher CV.

Moisture content: Plasma processes can generally treat waste with significantly higher moisture content than other thermal technologies. However, there is usually an upper limit on the moisture content to ensure that the energy required for waste degradation is within the design capabilities of the system (numbers of 75 wt% have been publicised in relation to some plasma processes). In addition, high moisture levels in the input waste obviously require higher energy input because significant heat is lost in evaporating water.

Ash content: High ash content waste usually has a low calorific value. We have already explained that low CV waste is not a problem for plasma. In fact the inorganic ash content of the waste is important to maintain stable and effective slag formation in plasma processes. Thus, some process suppliers may specify minimum ash levels in the input waste. Where the ash content is insufficient this is usually augmented by slag forming additives at a cost.

Aside from these technical aspects there are also questions whether plasma processing of MSW is economically viable and whether potential customers can be convinced about its operational availability. At the present time there is insufficient evidence to judge any of these definitively, which is discussed elsewhere in this report.

Thus, when considering large-scale MSW applications there are technology risks and economic uncertainties. At the present time there is insufficient evidence available to allow a definitive judgement – either way - about the applicability of plasma processes for processing MSW.

Leading Technologies

A plethora of plasma gasification processes have been marketed over the past few years as alternatives to incineration for treating residual MSW and SRF/RDF and our in-house database includes 55 such plasma gasification processes. These processes vary considerably in the level of provenness, scale, credibility of supplier, costs and hence 'bankability' (the ability to secure project finance on normal commercial terms).

WSP has used its in-house knowledge to identify the most credible processes and suppliers who could develop a fully commercial process within five years. The following table lists the technologies that we consider the most relevant to review for this Stage 2 report.

Table 2-15-1: Leading plasma gasification technologies/companies

| Plasma Gasification Technology | Country | Syngas | Slag | Commentary |
|--------------------------------------|---------|--------|------|---|
| Advanced Plasma Power (APP) | UK | ✓ | ✓ | Developing a process that combines the EPI fluidised bed gasification process (USA), which is now owned by Outotec (Finland) and the Tetronics plasma electrode melting system (UK). Pilot plant operated at the company's own facility in Swindon, UK. The Outotec gasifier is a proven concept with a number of plants built in the USA and the Tetronics plasma melter has been applied in several facilities in Japan and Taiwan. The two technologies have not yet been integrated into a fully commercial process. APP appears to be focussing on RDF to power applications but have not yet built a commercial facility. |
| AlterNRG | Canada | ✓ | ✓ | Canadian company that is pursuing opportunities to use its plasma gasification technology, (gained via its acquisition of Westinghouse Plasma Corporation). The combined team has significant experience in both gasification and plasma technologies. Currently developing projects to convert MSW to electricity via gas engines but AlterNRG's scope of supply is limited to the gasification island. The company has recently signed a joint development agreement with Air Products who is proposing to build a large plasma gasification plant in Teeside, UK. |
| Environmental Energy Resources (EER) | Israel | ✓ | ✓ | Promotes a plasma gasification technology that was developed in Russia in the early 1990's. A plant has been operated in Russia by Radon. The process is designed to treat about 40-250 kg/h (c. 1 – 6 tonnes per day [tpd]) of solid waste. EER has built a 12 to 20 tpd (c. 3600 to 6000 tpa) MSW demonstration plant in Israel using the Radon process design with plasma torches from another plasma supplier and this plant has undertaken continuous trials. They refer to their process as Plasma Gasification Melting (PGM). |

| Plasma Gasification Technology | Country | Syngas | Slag | Commentary |
|--------------------------------|---------|--------|------|--|
| Europlasma | France | ✓ | ✓ | <p>Builds and markets non-transferred arc plasma torches and melting systems for ash vitrification and hazardous waste treatment under a license arrangement with Aerospatiale (now EADS - European Aeronautic Defence and Space Company). Has development facility at which considerable trials have been conducted on wide range of applications.</p> <p>The technology is being used at four incineration facilities in Japan for ash vitrification. Has also built a facility in Bordeaux, France for processing a mix of hazardous inorganic wastes including asbestos and fly ash.</p> <p>Developing a concept called CHO-Power. A project has been announced in Morcenx, France, with a design capacity of 150 tpd of RDF and construction has commenced with the plant due to come on-stream in 2012. The technology is based on a grate gasifier developed by Bellwether, a German company, who has built one plant in Romania.</p> |
| InEnTec / S4 Energy Solutions | USA | ✓ | ✓ | <p>US company that has developed a plasma gasification system called the PEM (Plasma Enhanced Melter), which is one of the few that use a transferred arc plasma with graphite electrodes instead of plasma torches.</p> <p>Three PEM plants are operating on a commercial basis in the USA and Japan ranging in scale from 4 tpd (c. 1200 tpa) to 10 tpd (c. 3000 tpa) processing medical and industrial wastes.</p> <p>A subsidiary company, InEnTec Chemical, a JV with Lakeside Energy, has constructed a chemical waste disposal facility at Dow Chemical in the USA, which it has built on a BOO (Build, Own & Operate) basis. The JV company is pursuing the market for plasma processing of chemical wastes.</p> <p>A JV has also been formed with Waste Management Inc. (S4 Solutions) to pursue the market for plasma gasification of MSW to produce ethanol and other biofuels.</p> |

| Plasma Gasification Technology | Country | Syngas | Slag | Commentary |
|--------------------------------|---------|--------|------|---|
| Plasco Energy | Canada | ✓ | ✓ | <p>Formerly called Resorption Canada Limited (RCL), Plasco is a privately owned company focused on the promotion of a plasma gasification process for treating mixed industrial wastes, MSW, biomedical wastes and ASR. Plasco Energy Group was formed in the spring of 2005 from two companies, RCL Plasma and Plasco Energy Corporation.</p> <p>A 100 tpd demonstration facility has been operating intermittently since summer of 2007 in Ottawa, Canada.</p> <p>The company has announced plans for a 150,000 tpa plasma gasification facility in Ottawa that will process the city's residual waste. They have also announced three more projects in Canada, Japan and the Bahamas.</p> <p>In Europe, Plasco has formed a JV (Hera Plasco) with Spanish company Hera Holdings for the European market. HERA, an environmental and waste management company with operations in Spain and South America, has had a development partnership with Plasco. We understand that they were involved in the development of the facility in Ottawa. They have also operated a plasma pilot plant near Barcelona and are actively promoting the technology in Europe.</p> |

Source: WSP analysis

Brief Review of Each Technology

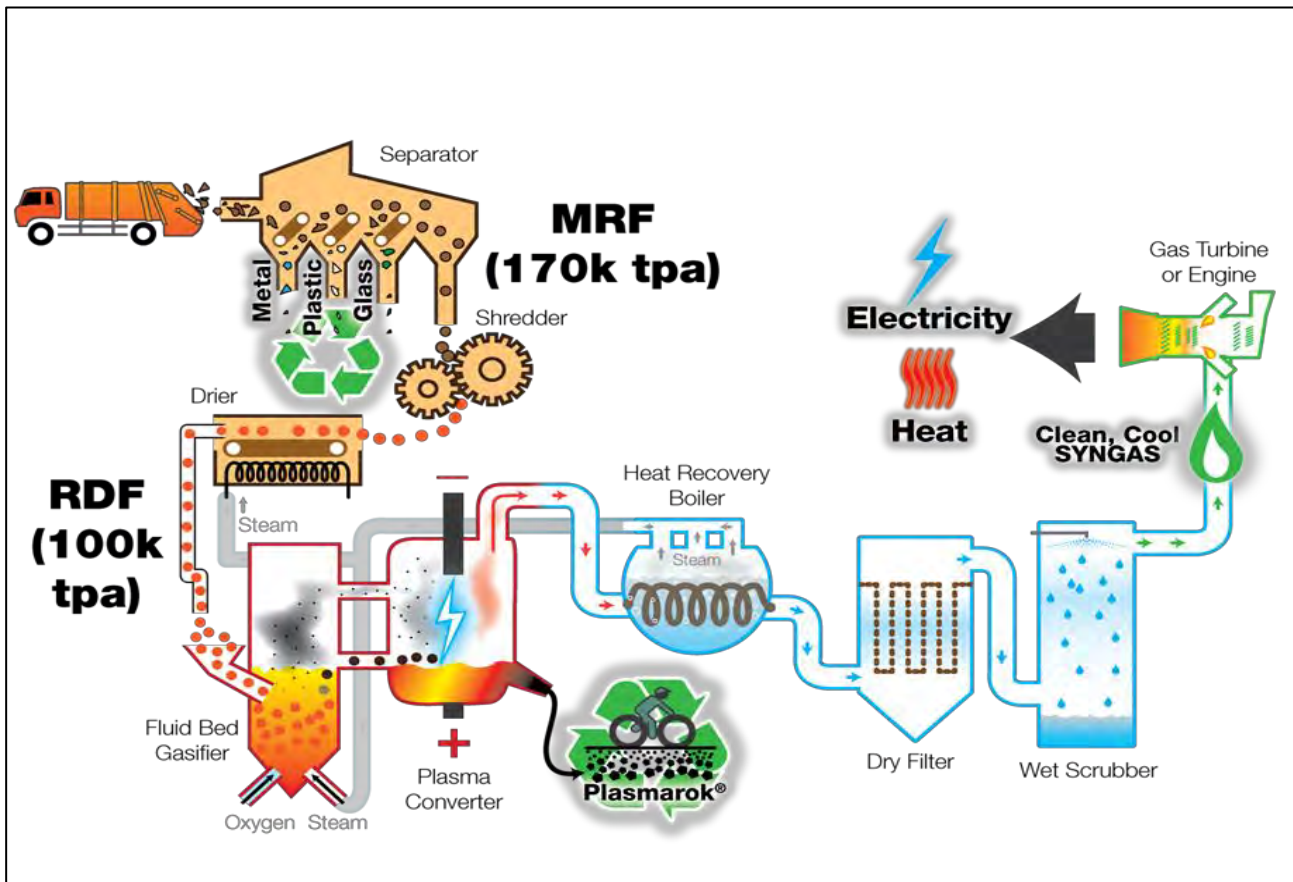
Advanced Plasma Power (APP)

Advanced Plasma Power Limited (APP) is a UK based waste to energy company which owns a technology for converting MSW and C&I waste into clean, local energy with low emissions and virtually no residues sent to landfill. It was founded in November 2005 to commercialise the proven Gasplasma technology originally developed by Tetronics Ltd, a specialist plasma company and APP's sister company. The technology comprises the combination of a fluid bed gasifier and a plasma arc in a secondary chamber creating a syngas that the company claim is clean enough to fuel gas engines directly.

As a spin off from Tetronics, APP has built on their expertise in plasma technology and developed an advanced thermal gasification process which comprises a conventional bubbling fluid bed gasifier followed by a plasma arc treatment stage. A prepared solid recovered fuel (SRF) is fed to the gasifier and the raw syngas is subsequently treated in a plasma conversion stage where the problematic tarry species, contained in the syngas, are effectively cracked and reformed to produce a syngas comprising primarily carbon monoxide and hydrogen. After conventional cleaning of the syngas to remove particulates and acid gas contaminants the syngas may be fed to gas engines or turbines. The process has been extensively tested and proven at APP's site in Swindon.

The basic generic process concept for an WtE facility using the Gasplasma technology which converts about 170,000 tonnes per annum of mixed waste, initially into Refuse Derived Fuel (RDF), and then into electrical power and heat energy, exporting renewable electrical power to the national grid is shown in the diagram below:

Figure 2-15-1: Schematic of the APP Gasplasma process



Source: APP

RDF is fed into the gasifier with steam and oxygen (in the absence of air). The process conditions are maintained by the control of oxygen, steam and RDF feed rate. This process provides sufficient heat to maintain the fluid bed temperature and produce a “crude syngas”. The syngas contains significant quantities of long chain and aromatic hydrocarbons which would condense as tars and residues if allowed to cool.

The ash component of the RDF is automatically removed from the base of the gasifier through the bed screening process and is conveyed to a hopper where it is metered into the plasma converter. There are no residues, chars or ash removed at this stage of the process.

The crude syngas is transferred from the gasifier to the plasma converter via a refractory lined duct. In the centre of the plasma converter is a graphite electrode from which a thermal plasma arc is generated. The syngas is exposed to elevated temperatures and intense ultra-violet light. The effect is to “crack” and reform the tars and chars contained in the syngas into their basic composition of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2) and water (H_2O).

The ash and dust particles associated with the syngas drop out of the gas stream and are incorporated into a molten slag pool which builds up in the base of the converter. This molten material is continuously removed from the plasma converter via an overflow weir and cooled for use as a vitrified and stable material. This material has been approved by the UK Environment Agency as a product and is trademarked under the name Plasmarok.

The gas cooling system comprises a heat recovery boiler designed to reduce syngas temperatures from 1,200°C to 160°C and generate saturated steam at 10 bar(g) pressure. The basis of the design is a water tube boiler using proven techniques employed in the energy from waste industry with specific attention given to the materials of construction to ensure long service life and to minimise down time caused by fouling and corrosion. The steam generated is used in the Gasplasma process; surplus steam is used for local heating duties or export.

The dry gas cleaning system, operating at 150 to 180°C, removes fine particulate materials from the syngas stream, neutralises acid gases and removes heavy metal vapour. The syngas passes to the ceramic particulate filter via an insulated duct into which the reagents sodium bicarbonate and activated carbon are injected. The duct provides sufficient residence time and turbulence to allow good reaction and collection, providing high capture rates for acidic components and volatile metals. Particulate matter, including the by-products from the reagent reactions, is trapped on the ceramic filter elements and periodically removed using a nitrogen reverse pulse system.

From the dry gas cleaning phase, the syngas is cooled by direct contact with scrubbing liquor in a condenser scrubber. The unit is used to drop the syngas temperature to circa 30°C. The condenser operates as an acid scrubber, absorbing ammonia. To ensure complete absorption and neutralisation of the ammonia the pH is maintained as acidic.

The gases are passed through a second, alkaline, scrubber to remove acid gases - in particular sulphur dioxide and hydrogen sulphide. The hydrogen sulphide is chemically oxidised to produce a stable effluent. The syngas leaving the wet cleaning system is clean syngas ready for use in power generation.

The effluent from this scrubber and the condensate from the condenser scrubber are discharged from the system for neutralisation, treatment and discharge to sewer.

The Power Island is fed by the clean syngas from the gas production system and generates electrical power from direct combustion of the clean syngas in gas engines or turbines.

The exhaust gas from the engine or turbine passes through a system of emissions control catalysts which ensure that the emissions comply with WID. Following the emissions control catalyst, heat is recovered from the hot exhaust gas and superheated steam is generated at medium pressure for use in a steam turbine.

No environmental performance data for the APP is available in the public domain. No commercial plant has yet been built and there no reliability or availability data exists.

The company has announced a project in Belgium, in partnership with a Belgian waste management company to min an existing landfill and convert the material removed into Plasmag and electricity. The plant is still in the design stage.

AlterNRG

AlterNRG is a Canadian company, based in Calgary, who acquired Westinghouse Plasma Corporation (WPC) in 2007. The company is offering their plasma gasification process for MSW/RDF applications with a conventional steam cycle energy generation section and are also trying to develop an IGCC process with syngas cleaning and direct electricity conversion via gas engines or gas a turbine.

The heart of the process is the Plasma Gasification Reactor (PGR), which is based on the WPC cupola, which is a vertical shaft furnace of a type conventionally used in the foundry industry for the re-melting of scrap iron and steel. It is internally lined with the appropriate refractory to withstand high internal temperatures and the corrosive operating conditions within the reactor. The preliminary size of the standard PGR is 9.7 metres outer diameter at its widest point and 19 metres overall height.

The cupola forms the base of the plasma gasification reactor and has been proven at commercial scale for various melting applications. A coke bed is created within the cupola using metallurgical coke (met coke) to absorb and retain the heat energy from the plasma torches and provide the environment for melting inorganics (metal and mineral content of the waste).

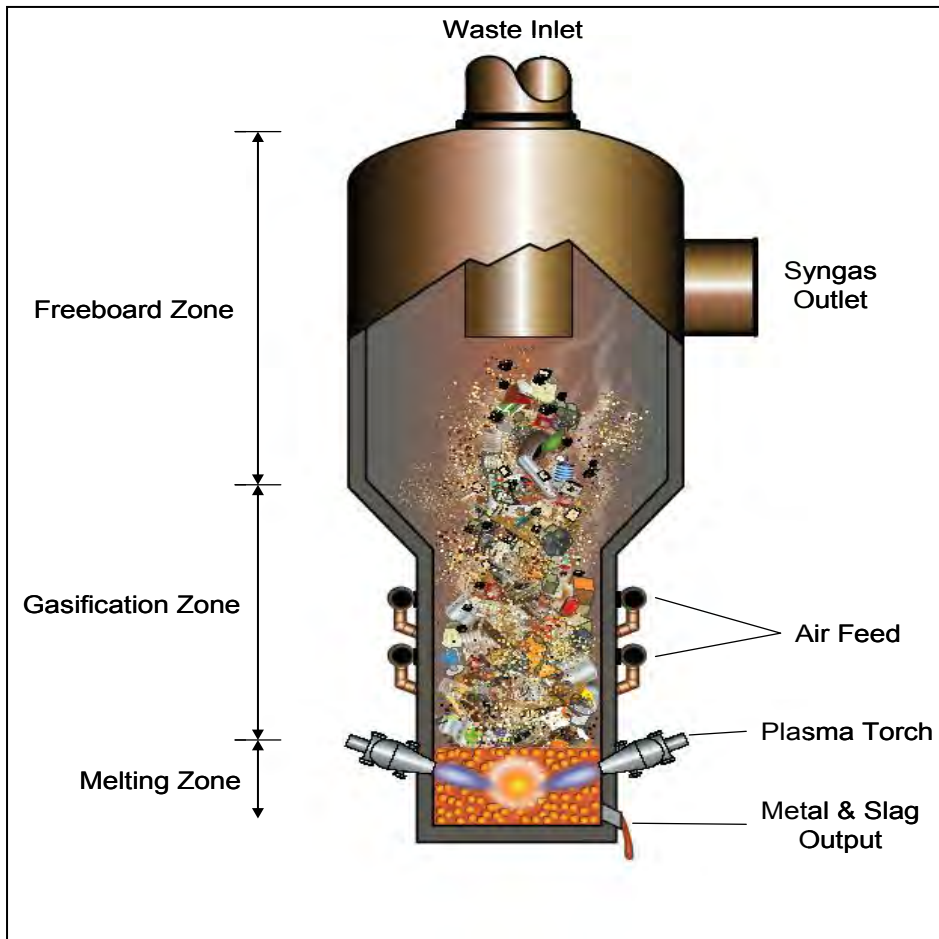
In this design the waste does not pass through the plasma torch. Indeed the plasma torches do not impinge directly on the input waste. Instead, the torches are used to provide the high temperatures required by the cupola. We refer to this design concept as Plasma-assisted Gasification. In this concept, the role of the plasma torches is to create a stream of very hot air (the plasma plume) which provides an intense input of heat energy into the reactor, supplemented by heat released by the met coke which is slowly consumed.

It should also be noted that a number of other proponents of plasma-assisted gasification waste processes claim that the MSW 'sees' a temperature of $\approx 20,000^{\circ}\text{C}$ and is therefore completely destroyed by being 'zapped' into simple molecules. In fact within the Alter NRG/WPC design the temperature of the plasma plume

would be between 5,000 and 7,000°C and the bulk temperature within the base of the reactor (cupola) about 2,000°C – far lower than the 20,000°C referred to earlier. The actual operating temperatures are sufficient to drive the gasification reactions and break down tars and higher molecular weight compounds into CO and H₂ and it is unfortunate that these claims that are made by other developers create a false impression of how plasma assisted gasification processes work.

The plasma torches therefore are energy input devices and the plasma assists the gasification reactions to take place. The electrical energy input to the plasma torches is also used as a control parameter to accommodate and counteract the expected variations in waste CV.

Figure 2-15-2: Schematic of the Plasma Gasification Reactor



Source: Alter NRG

The gasification reactions will convert the organic component of the MSW/tyre feedstock into a syngas which exits at the top of the PGR while the inorganic components are converted into a molten slag that exits at the bottom of the reactor at about 1,650°C and is sent to the slag handling system where recoverable metals are removed. The PGR operates with very high temperatures in the lower portion of the reactor and both oxygen and steam will be injected into the process. The high temperatures also significantly increase the kinetic rates of the various chemical gasification reactions.

The syngas will exit the PGR at 890°C – 1100°C at near atmospheric pressure. It will be quenched and cleaned for various downstream uses.

The process requires an oxygen supply and depending on the scale this could be supplied by an oxygen PSA³⁴ unit or a cryogenic ASU³⁵ would be required.

The syngas will be cleaned in a multi-stage process, the number of stages being dependent on how clean the syngas needs to be for the particular utilisation and conversion process specified in each specific project. These multi-stage elements can add considerably to the capital costs and incur significant operating costs for the disposal of secondary residues.

Three plants were built in Japan for waste management applications. The plants at Yoshii, Utashinai and Mihama-Mikata were built by Hitachi Metals under licence from WPC for the processing of MSW and ASR³⁶. The operating plants using the WPC plasma technology, prior to the acquisition by AlterNRG, are summarised in the table below.

Table 2-15-2: Selected reference plants using the WPC plasma technology

| Location | Duty | Plant capacity (tpd) | Treatment capacity (tpa) | Start-up |
|--|--|------------------------|--------------------------|----------|
| Yoshii, Japan [#] | Plasma gasification of MSW | 24 tpd | 7,200 ^{**} | 1999 |
| Utashinai, Japan | Plasma gasification of MSW + ASR | 180 tpd ^{***} | 49,500 ^{**} | 2003 |
| Mihama-Mikata, Japan | Plasma gasification of MSW + dried sewage sludge | 22 tpd ^{****} | 6,600 ^{**} | 2003 |
| [*] depending on feed material ^{**} calculated by Juniper assuming 300 days operation per year ^{***} 50% MSW + 50% ASR ^{****} 80% MSW + 20% dried sewage sludge [#] no longer operating | | | | |

Source: Analysis of information supplied by AlterNRG

Air Products has announced they are planning to build a major plasma gasification plant in the North East of England using AlterNRG's plasma reactor. The plant is still in the design phase but obviously Air Products believes the technology is viable.

³⁴ Pressure Swing Adsorption

³⁵ Air Separation Unit

³⁶ Auto Shredder Residue

The following emission to air data was obtained from the two operating Japanese plants:

Table 2-15-3: Air emission data from Japanese plasma gasification facilities

| Pollutant | Unit ¹ | EU criteria ¹ | Utashina ² | Mihama-Mikata ³ |
|--|-------------------------|--------------------------|-----------------------|----------------------------|
| Dust | mg/Nm ³ | 9.0 | < 0.01 | < 16.0 |
| SO ₂ | mg/Nm ³ | 45.0 | < 5.7 | 0.3 – < 14.3 |
| HCl | mg/Nm ³ | 9.0 | 22 – 50 | 140 – 151.5 |
| NOx | mg/Nm ³ | 180.0 | 24 – 81 | 135.5 – 165 |
| Dioxins | ng-ITEQ/Nm ³ | 0.09 | 0.002 – 0.0098 | 0.00004 – 0.0024 |
| 1 – all data at 12% O ₂ , 101 kPa, 273K 2 – processing ASR + MSW (50:50) 3 – processing MSW | | | | |

Source: AlterNRG

The data for HCl emissions is well above that allowed by EU WID, and NOx levels at Mihama-Mikata were close the EU limit. The NOx values were probably a result of processing sewage sludge but for a new plant we believe that AlterNRG would be able to design the flue gas cleaning part of the process to ensure that EU WID limits were met.

Hitachi Metals stated that the average annual availability (operational hours) was 83%. This is lower than conventional combustion but is a function of more novel technology, Japanese operational methodologies and the fact that ASR is a troublesome fuel causing significant slagging and fouling.

Indications from AlterNRG give a capex number (highly preliminary) of about US\$65 million for a two line plant to process 120,000 tpa of waste.

Environmental Energy Resources (EER)

The EER process is a high temperature plasma-assisted gasification process. The technology is a derivative of the technology developed in Russia by the Kurchatov Institute and SIA Radon for the destruction of low level radioactive wastes (LLRW). EER, which was formed in 2000, and their team of scientists and engineers based in Israel worked with their Russian counterparts to develop the design and build a demonstration plant at the Yblin landfill site in Israel, which is located in the densely populated Haifa region. This facility aims to demonstrate that their technology is a practical solution for processing MSW-derived fuels.

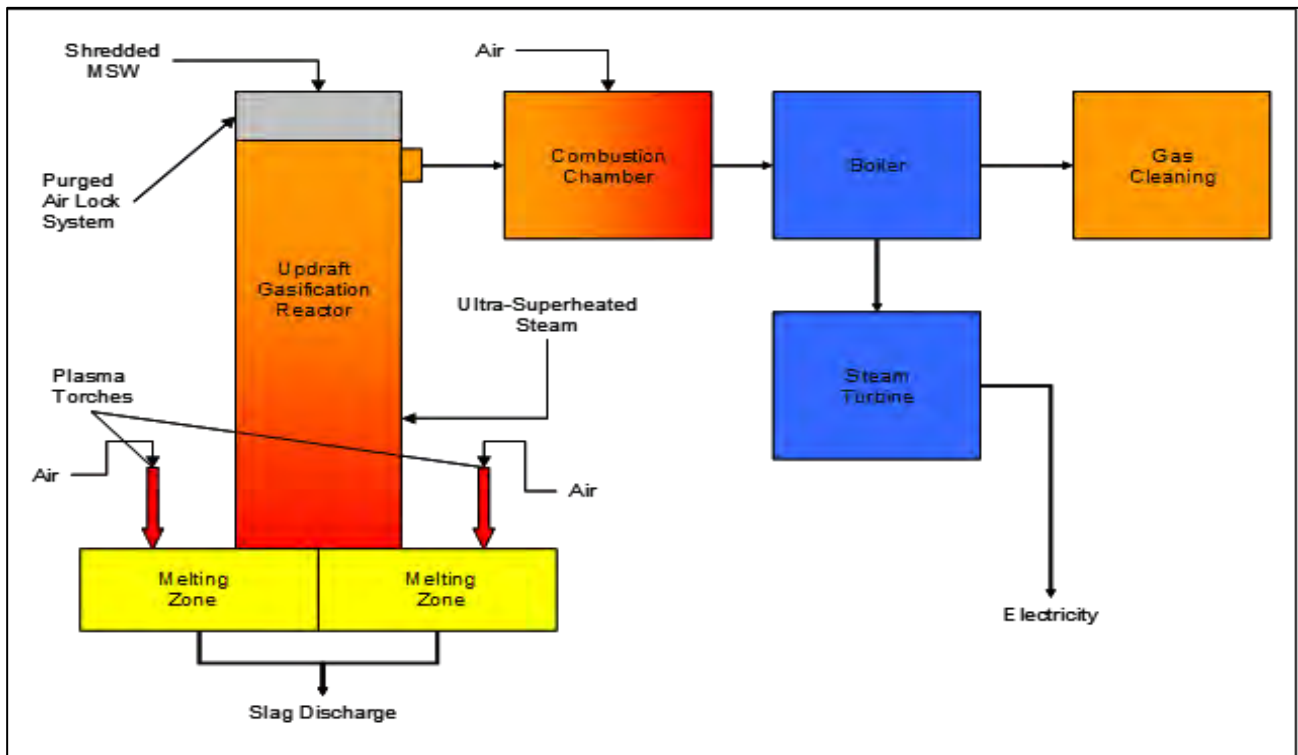
The specific variant of gasification used in the PGM (Plasma Gasification & Melting) process is, so far as we are aware, unique. However, certain elements of the process have been used before in different applications, as discussed below, and hence the technology risk is mitigated to some extent by experience elsewhere.

At the heart of the PGM process is an updraft gasification reactor in which the melting of inorganics at the base of the gasifier is assisted by the energy input from plasma torches.

As with other gasifiers of this type the waste enters at the top and flows downwards under gravity. The intention is to maintain a column of waste over the entire height of the reactor, which is achieved by a series of level indicators. The temperature increases from the top to the bottom and the waste undergoes various reactions including drying, pyrolysis, gasification, combustion of char before, finally, the inorganic content is melted at the bottom and converted into a vitreous slag.

The Yblin plant incorporates a double air lock feeding arrangement with a screw feeder. In our recent discussions EER informed us that they were now considering using a ram feed system. In response to our clarification questions they informed us that the final choice for the feeding system for the first commercial plant had not yet been made.

Figure 2-15-3: Schematic representation of the EER plasma gasification process



Source: interpretation of EER information

Part of the energy input needed to effect the melting of the inorganic materials is added by the plasma torches. This is an advantage of the PGM process because it avoids the use of pure oxygen with its associated high costs of production and handling, but EER need to demonstrate that the use of plasma torches in this way can meet reliability and cost thresholds related to the torches themselves. An updraft gasifier processing MSW/RDF with integrated plasma torches to provide the energy input to melt inorganics has not been fully demonstrated before although the Russian plant has demonstrated successful operation with 'MSW-like' waste feeds and therefore EER could gain a 'first mover' advantage.

In addition to the energy provided to the gasification reactions by radiation from the pool of molten material at the base, auxiliary energy input is required to maintain the endothermic (energy input) reactions within the reactor which will be provided by ultra-superheated steam (USS) with a temperature of 1,000°C. The USS (steam = H₂O) also provides additional hydrogen to take part in the gasification reactions.

The inorganic content of the waste flows from the base of the updraft gasifier into the melting chamber. The original design (as installed in Russia) of the melting chamber has a one sided plasma chamber whilst at Yblin this has been modified to a symmetrical design with plasma chambers on opposite sides, which is serviced by two pairs of plasma torches (for Yblin - supplied by the Canadian company, Pyrogenesis). The temperature within this chamber is maintained between 1200 and 1500°C by the plasma torches.

The design currently proposed for future commercial plants will produce cleaned syngas. The design for the proposed syngas cleaning systems employs the following processes:

- a hot cyclone to remove particulates greater than 10 microns;
- a two stage direct contact scrubber to remove as much of the tar loading as feasible. A hydrocarbon oil is used as the scrubbing absorbent;
- further processes (which are considered by EER to be proprietary) are then used to reduce the particulate and tar loading in the syngas to very low levels;
- optionally, a proprietary desulphurisation process that will convert hydrogen sulphide (H₂S), formed in the gasifier from sulphur present in the waste feed, into elemental sulphur.

EER's preferred desulphurisation technology is the Thiopaq process to be supplied by Houston-based NATCO. This process was originally developed by Paques and is a biological process for removing H₂S from biogas produced by anaerobic digestion processes. The bioreactor is there to allow a population of bugs to grow and contact the iron sulphide produced in the desulphurisation reactor and convert it to elemental sulphur. The bio-reactor sieve tray column also regenerates the sorbent to send back to the H₂S absorber.

Some of the gas cleaning residues, particularly the particulate matter and heavy tars, would be combined with spent sorbent and recycled into the high temperature zone of the gasification reactor. This would allow the energy content of the tars and the carbon in the flyash to be recovered by the process. The cleaned syngas then passes to a gas holder.

We understand that, a commercial scale plant would use technology from suppliers with relevant experience to clean the syngas and use gas engines to produce electricity. An additional process (ORC³⁷) will recover energy from the hot engine exhaust gases thereby increasing the overall energy recovery efficiency of the plant.

Europlasma CHO-Power

Europlasma draws its plasma technology experience from the European Aeronautic Defence and Space Company (EADS). The company was established in 1992 and is a publicly traded company (@ Euronext Paris) with about 160 employees.

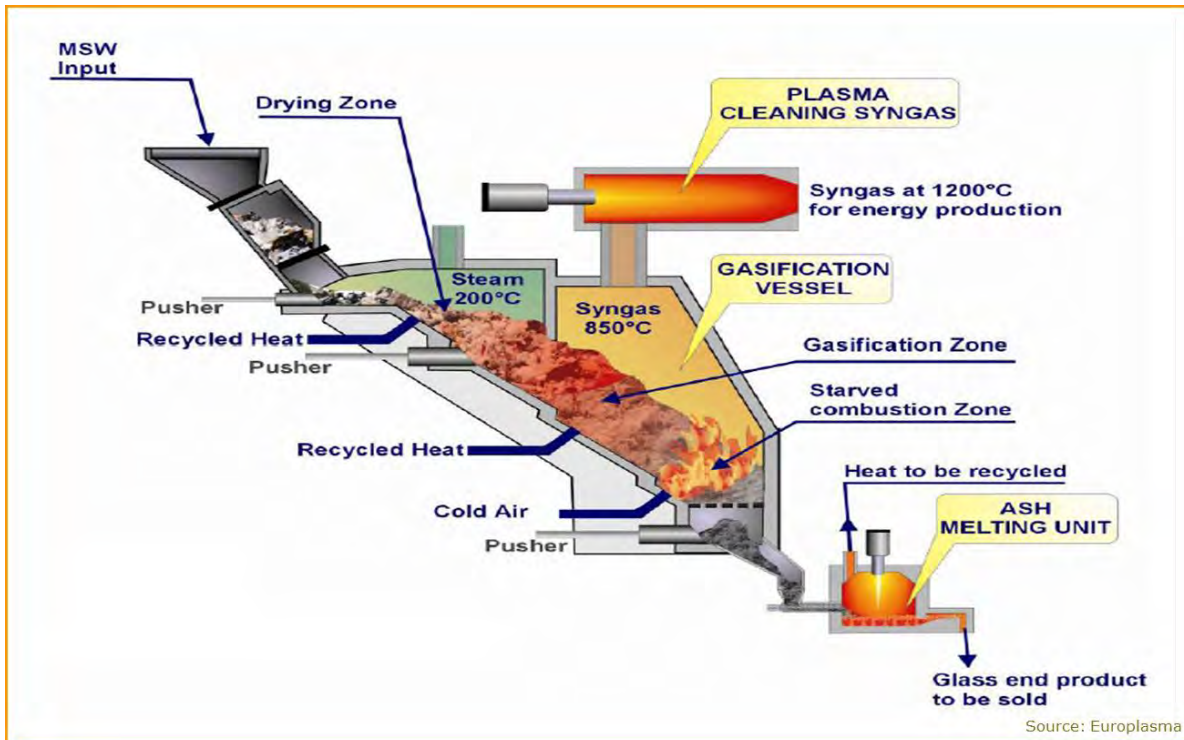
Europlasma specialises in the use of plasma technology for industrial applications, most notably for hazardous waste destruction (vitrification). The company constructs plasma torches and to date has sold 32 plasma torches delivered for various applications in the metal industries and for hazardous waste destruction. For example, Europlasma has sold plants for ash melting and vitrification at MSW incineration plants in France (Cenon) and Japan (Imuzu). They have also built and operate an asbestos waste destruction plant at Morcenx, France. The company is currently expanding its business into energy-from-waste and has developed the CHO-Power process.

The CHO-Power process comprises a primary gasification stage based on a moving grate system from which syngas is produced which passes through a plasma polishing reactor where the high temperature and oxygen free conditions 'crack' the higher molecular weight molecules and any liquid hydrocarbons present to produce a cleaned syngas comprising CO, H₂ and traces of CH₄. As an optional addition a second plasma reactor can be incorporated to melt the ash (inorganic) residues from the gasifier and produce a vitrified slag that could be recycled into civil engineering applications.

The cleaned syngas is then directly converted to electricity via gas engines.

³⁷ Organic Rankine Cycle

Figure 2-15-4: Schematic diagram of the CHO-Power process



Source: Europlasma

Europlasma has constructed their first commercial facility in Morcenx, near Lyon, France. The facility will treat 37,000 tpa of local industrial waste and 15,000 tpa of wood chips from the region. The plant will produce 12 MWe of electricity to be exported to the grid and 18 MWth of heat that will fuel a woodchips drier.

There is no emission data to review but as a European company having built their first plant in Europe they know the Morcenx plant will have to meet the emission limits of the EU WID.

The process has not yet demonstrated prolonged continuous operation at a commercial scale and there is no data on annual availability hours at this time. Europlasma has supplied their plasma melting system to a number of leading incineration companies in Japan for bottom ash melting duties and therefore the company would be confident about that part of the process. The performance of the grate gasifier is unknown at this time and Europlasma will need to demonstrate 6 months of continuous operation before the process could be considered fully proven.

The investment for the Morcenx plant was in the order of 40 million Euros.

InEnTec / S4 Energy Solutions

InEnTec's technology builds on extensive US Department of Energy-sponsored research at the Massachusetts Institute of Technology (MIT) and Battelle Pacific Northwest National Laboratory (PNNL). At MIT, plasma applications have been investigated extensively at the Plasma Science and Fusion Centre (PSFC), MIT's largest on-campus laboratory. In 1991, the PSFC undertook a research program to explore the use of plasma for the treatment of radioactive waste at United States Department of Energy (US DOE) sites. The high temperature of plasmas and their ability to process waste without the adverse environmental impacts encountered with incineration made plasma technology a very attractive option. MIT, together with an industrial subcontractor, formed a collaborative effort with PNNL.

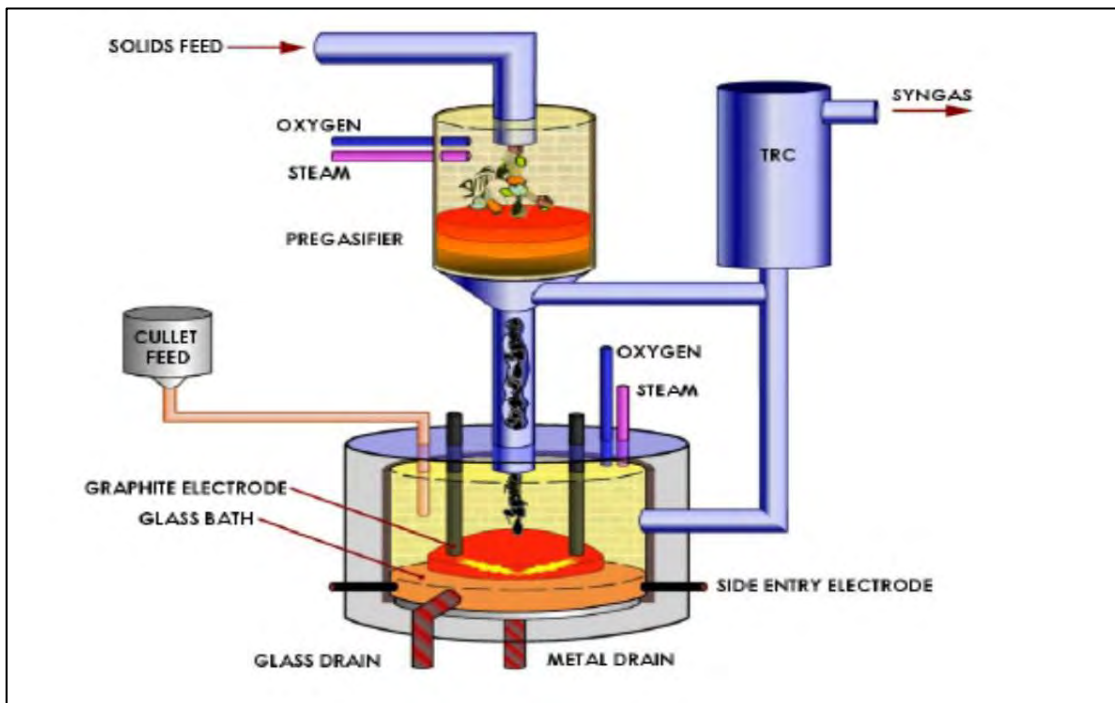
The MIT - PNNL effort constructed a research device at MIT for studies of plasma-arc waste treatment. The system employed a single graphite electrode and was used for a variety of tests that confirmed the basic attractiveness of plasmas for treating mixtures of radioactive and hazardous waste. In 1995, this research program was evaluated by the US DOE, which concluded that the graphite electrode DC arc-plasma system was the most promising approach for meeting its needs to treat mixtures of hazardous and radioactive waste.

Integrated Environmental Technologies, LLC (IET) was spun out of this research activity in July 1995, as was the exclusive rights to the PEM technology. In 1996, InEnTec opened its Technology Centre in Richland, Washington, where development efforts have led to the successful commercialisation and deployment of PEM systems around the world.

In 2008, the company changed its name to InEnTec LLC and moved its headquarters to Bend, Oregon.

The InEnTec Plasma Enhanced Melter (PEM) system has integrated the technologies of plasma melting and glass melting to create a concept that provides the capability in converting waste into useful products, thereby maximising the potential for recycling. InEnTec has developed a two-stage process using a pre-gasification stage (downdraft) followed by a PEM reactor.

Figure 2-15-5: Schematic of the InEnTec plasma gasification process



Source: InEnTec LLC

The pre-gasifier (downdraft) acts as a “preliminary” processing zone in which a majority (approximately 80%) of the organic portion of the feedstock is converted to syngas. The remaining feedstock, consisting of inorganic materials (dirt, glass and metal), carbon, and other unprocessed organics pass through to the outlet at the bottom of the pre-gasifier and into the PEM reactor.

The remaining feed materials from the pre-gasifier are dropped onto a molten glass surface near the plasma-arc zone, within the PEM reactor. The plasma arc provides the intense energy needed to rapidly gasify the remaining organic materials, converting them to syngas, which exits the PEM reactor and flows to the Thermal Residence Chamber (TRC), which is designed to provide additional residence time at a high enough temperature to fully process any remaining organic materials present in the syngas and allow the gasification reaction to reach equilibrium.

The primary power supply system for the PEM introduces both joule-heating and plasma energy into the reactor by means of separate power supplies for the DC plasma and the AC joule heating system. The DC

power is used to produce the plasma-arc, which provides most of the energy for gasification of the feed material. The independent AC power heats and maintains the glass bath temperature, allowing the plasma-arc power to be focused on the gasification process and not on maintaining the molten pool.

The syngas leaving the TRC is cleaned in a series of standard processes to prepare it for use in any final products. The company state that the syngas may be used for a variety of applications such as electricity generation, production of liquid fuels or conversion to industrial products such as hydrogen.

S4 Energy Solutions LLC, founded in 2009 as a joint venture between InEnTec and Waste Management Inc. and now wholly owned by InEnTec, designed and built a waste processing facility using the InEnTec two-stage plasma gasification process. The facility converts MSW into clean syngas. The syngas is being used to demonstrate and prove various end-uses, which will include hydrogen production. We understand the plant has been operating for about 10 months and the company claims good performance.

Figure 2-15-6: The S4 Solutions plasma gasifier at Arlington, Oregon



Source: InEnTec website

Plasco Energy

Plasco is a Canadian waste conversion and energy generation company that was formed in 2005 by a merger with Resorption Limited. The company is privately owned and has 100+ employees. The company's main activities are in North America but they have formed a strategic alliance with Hera Holdings, a large Spanish waste management company, for the European market.

The process employs plasma torches to clean up the produced syngas and a plasma torch to melt the inorganic residues.

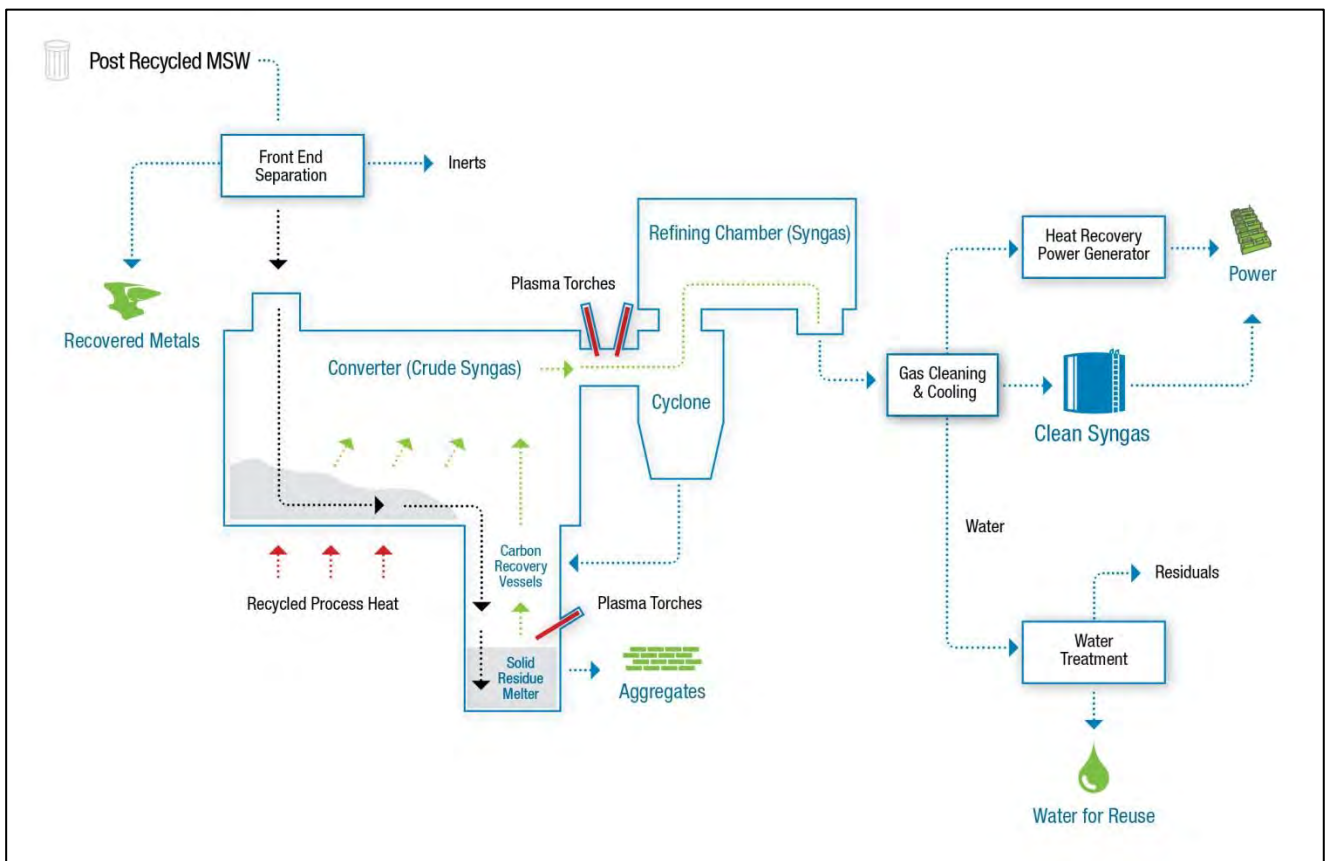
The MSW stream enters the conversion chamber where the waste is converted into a crude synthetic gas (syngas) using recycled heat. The crude syngas that is produced flows to the refinement chamber where plasma torches are used to clean-up the gas by cracking tar compounds formed in the gasification process.

The syngas is then passes to the cleaning processes to remove dust, sulphur, acid gases and heavy metals found in the waste stream.

The syngas is used to fuel gas engines that generate electricity directly with a higher efficiency than the steam cycle. Waste heat recovered from the engines is combined with waste heat recovered from cooling the syngas in a waste heat recovery boiler to produce steam. The steam can either be used to generate additional electricity using a turbine (combined cycle generation), or it can be used for industrial processes or district heating (cogeneration).

The solid residue from the conversion chamber is sent to a separate high temperature vessel equipped with a plasma torch where the solids are melted. The plasma heat is used to stabilise the solids and convert any remaining volatile compounds and fixed carbon into additional syngas, which is fed back into the conversion chamber. Any remaining solids are then melted into a liquid slag and cooled in a water bath to produce small slag pellets. The slag pellets are an inert vitrified residue that could be used as construction aggregate. The company claims leach testing has been conducted on the vitrified slag and have confirmed that the slag does not leach.

Figure 2-15-7: Schematic of the Plasco Energy gasification process



Source: Plasco website

The first commercial scale project was built in Ottawa, Canada in 2007. The plant is designed to process about 30,000 Tpa of MSW and operates as a demonstration plant.

We understand that Plasco entered into a partnership with the City of Ottawa in April 2006 for the construction of the commercial scale demonstration facility across from the City's Trail Road Landfill. The facility has a small footprint (3 acres) and was built on existing landfill space.

Plasco Trail Road was constructed for several purposes:

- to demonstrate Plasco's technology at a commercial scale;
- to produce environmental emissions data to create a database of information for future projects;
- to improve the operational and environmental performance of the process;

- to validate Plasco's engineering models used for commercial designs.

The Plasco Trail Road facility is operated on a campaign basis which allows for maintenance and modifications to be performed. The plant is permitted under specific regulations that allow operations and testing to proceed within defined limits and controls.

Since the facility first began processing residual MSW after the City of Ottawa's recycling activities, operations at the plant have successfully demonstrated:

- electricity generated by GE Jenbacher engines sold to a local utility;
- acceptable environmental performance;
- production of commercially acceptable vitrified slag;
- treatment of waste water on-site.

At Plasco Trail Road, the air emissions are associated with exhaust gases from the gas engines used to generate electricity. Plasco claims to have invested in the best available gas cleaning technologies to ensure that the syngas is clean prior to delivering it to the engines.

Table 2-15-4: The emission profile at Plasco's Trail Road facility

| Parameter | Units | US EPA 40 CFR 60 Eb | EU | Site limits | Site actuals |
|--|--------------------------|---------------------|-------|-------------|--------------|
| Dust | mg/Nm ³ | 14 | 9 | 17 | 0.73 |
| Total Organic Carbon | mg/Nm ³ | - | 9 | 66 | 0 |
| HCl | mg/Nm ³ | 27 | 9 | 27 | 0.28 |
| SO ₂ | mg/Nm ³ | 56 | 46 | 56 | 38 |
| NO _x | mg/Nm ³ | 202 | 183 | 207 | 107 |
| Hg | µg/Nm ³ | 35 | 46 | 20 | 0.2 |
| Cd | µg/Nm ³ | 7 | 46 | 14 | 0 |
| Pb | µg/Nm ³ | 98 | - | 142 | 0.2 |
| Dioxins/Furans | ng I-TEQ/Nm ³ | 9 | 0.092 | 0.08 | 0.001 |
| <p>* Plasco Flare with Engine No. 1 exhaust (100% MSW) as submitted to the Ontario Ministry of Environment in Interim Source Test report (HCl, SO₂ and NO_x maximum 24 hr average during source test)</p> <p>Notes:</p> <ol style="list-style-type: none"> 1. All values are expressed at 11%O₂ and normal conditions (101.3 kPa, 25°C) 2. EU regulations combine Thallium with Cadmium and Lead with Class III Metals | | | | | |

Source: Plasco website

Other Technologies to Watch

Covanta Energy

The company has developed a 350 tpd (approx. 90,000 tpa) moving grate gasifier, which was operated for 12 months at one of the company's WtE sites in the US. The plant achieved an availability of > 95% during this trial period. We understand the process is ready for market roll-out in the USA.

Chinook Sciences

The company has developed a pyrolysis process producing syngas which is utilised via close-coupled combustion and produces power via the steam cycle or cleaned to fuel gas engines. The company has 7 operational plants in the US and Europe, which are relatively small scale, and is currently constructing a plant in the UK to process ASR (160,000 tpa).

Outotec (formerly Energy products of Idaho [EPI])

EPI acquired by Finnish company Outotec. EPI has supplied more than 100 fluidised bed combustion plants mainly for biomass and paper mill wastes. The company has developed a fluidised bed gasifier and an air staged gasification plant. They are very active in several markets including the UK.

WSP UK Limited

WSP House

London

WC2A 1AF

UK

Tel: +44 (0)20 7314 4647

Fax: +44 (0)20 7314 5111

www.wspgroup.co.uk

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