



APPENDIX C. CASE STUDIES



Alter NRG – PGVR

The Plasma Gasification Vitrification Reactor (PGVR) is a plasma-assisted gasification process commercialized by Alter NRG, a Canadian company, who has recently acquired Westinghouse Plasma Corporation (WPC), the original developer and a leading supplier of non-transferred arc (NTA) plasma torch technology.

The first generation of full-scale commercial PGVR systems has had a mixed success, with one small facility (Mihama-Mikata in Japan, 25 tpd) reporting nearly ten years of successful operation and a second large-scale facility (Utashinai 150-220 tpd) having being plagued by a series of design flaws and commissioning issues, ultimately causing the anticipated shutdown of the plant in 2013.

The second generation PGVR design – integrating all the modifications adopted to address earlier operational issues at the Utashinai facility – has since been installed successfully at one sites in India, with two other projects under development and has been selected for two facilities being installed at the Tees Walley Renewable Energy facility, developed by Air Products in the UK.

Technology development and commercialization

The Westinghouse Electric Corporation conducted early work on non-transferred arc (NTA) plasma torch applications at a 48 tpd pilot plant in Madison, Pennsylvania, still operating to this day as an R&D facility.

In the 1990s, Westinghouse and Hitachi Metals Ltd. joined forces to develop applications of the technology for processing MSW and biosolids, leading to the construction and operation of a demonstration facility in Yoshi, Japan commissioned in 1999.

The Yoshi facility was instrumental to develop operational experience and design information for projection to the first generation full-scale commercial concept of the Plasma Gasification Vitrification Reactor (PGVR). Following the experience at Yoshi, Hitachi Metals developed two commercial facilities in Japan: Mihama-Mikata (25 tpd, started in 2002) and Utashinai (150-220 tpd, started in 2003).

The Mihama-Mikata plant, a commercial success, has now over ten years of operation at full capacity. The Utashinai plant is instead being planned for shutdown in 2013 as a result of significant commissioning issues that have limited its operations and affected its profitability. Lessons learned at Utashinai have determined the improvements made towards the second generation of PGVR being commercialized today by Alter NRG Corp., which purchased Westinghouse Plasma Corporation and their technology in April 2007.

The company is actively pursuing opportunities for a range of potential applications of plasma technology, including waste-to-energy (MSW, biosolids and hazardous waste), co-gasification with coal, waste-to-ethanol to MSW and gasification of petcoke and other refinery residuals.

Two 70 tpd gasification facilities for hazardous waste have been commissioned recently in Pune and Nagpur, India. A substantial pipeline of other commercial prospects is also advertised on the AlterNRG website, with over 30 projects at different stages of development, from site selection to detailed engineering, including three projects in Australia claimed to be all past the site selection, feasibility study and feedstock agreement stages as of Q1 2011:

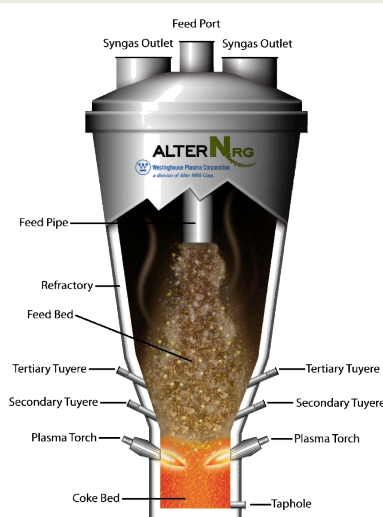
- a 50 mUSD waste-to-ethanol plant in Melbourne,
- a 30 mUSD waste-to-energy plant in Geelong, and
- a 32 mUSD waste-to-energy plant in Kwinana.

Phoenix Energy²⁵ commercializes the PGVR technology in Australia on a license from AlterNRG.

Process description

The schematic below represents the PGVR furnace, the core component of AlterNRG plasma gasification systems. The current generation design features a number of design improvements based on the lessons learned at the Utashinai EcoValley facility (see below).

Figure 78. Schematic of the Alter NRG PGVR²⁶.



²⁵ <http://www.phoenixenergy.com.au/> (formerly trading as Moltoni Energy).

²⁶ Adapted from (Willis et al. 2010)

In a typical plant waste-to-energy configuration the PGVR is combined with a waste pre-processing and feed system, a molten residue removal and handling system, a steam power generation island (boiler, turbine, condensers), and air-pollution control (APC) for flue-gas clean-up and handling.

Pre-processing

For solid materials (MSW and other residues), the Alter NRG system requires shredding of the materials to 15 cm top size. A moisture content of ~30% is desirable as the excess water turned into steam in the reactor promotes reforming of carbonaceous components to syngas.

Additional pre-treatment might be required for liquids, sludge to avoid jamming and ensure a continuous feed to the plasma reactors, as well as to avoid leaks and fugitive emissions when dealing with hazardous waste streams.

The high-temperatures in the plasma reactors pose some process control challenges. The implementation of rapid and effective feed shut-off systems is crucial to the safe operation of the plant when operating conditions deviate from the envelope defined by the operating permits.

Heating and conversion

Commercial PGVR units have diameter ranging from 1 to 4.6 m, with the volume above the bed of pyrolyzing waste designed to provide a gas residence time of about 30 s.

The gasifier chambers are operated at slightly sub-atmospheric conditions, with the plasma torches (2 to 4 depending on the unit) distributed radially along the lower sections of the reactor. This design allows for replacement/servicing of the torches without shutting down the unit.

AlterNRG supplies two types of PGVR units:

- the W-15 or Wolverine, rated at 170-250 tpd for waste and 120-300 tpd on biomass; and
- the G-65 or Grizzly, rated at 500-750 tpd for waste and 300-1000 tpd for biomass.

The water-cooled torches use air as the plasma gas and are rated for 1200 h of continuous duty. The torches are powered by a thyristor power supply providing a current controlled DC output. The plasma torches are supplied in three models (MARC 3A, 11H and 11L), with energy inputs and key characteristics listed in the Table below.

Table 71. Key characteristics of AlterNRG/Westinghouse plasma torches.

| | Torch model | | |
|---------------------------|-------------|----------|----------|
| | MARC 3A | MARC IIL | MARC IIH |
| Min rated power, kW | 80 | 350 | 860 |
| Max rated power, kW | 300 | 800 | 2400 |
| Max operating current, A | 400 | 1000 | 2000 |
| Max operating arc voltage | 860 | 950 | 1200 |
| Air flow, kg/h | 42 | 197 | 415 |
| Thermal efficiency | 70% | 85% | 85% |
| Diameter, mm | 89 | 45.7 | 45.7 |
| Length, mm | 18 | 35 | 35 |

SOURCE: (WPC 2013)

The plasma-heated gas stream from the torches is directed to a bed of foundry coke and limestone fed with the waste. The coke mixed with the waste (about 4% of the total mass input) has two key functions: it provides support for the waste bed as it pyrolyzes and vitrifies, and offers a porous surface through which the molten inorganic fraction of the feed can drain to a discharge point.

Further, the superheated combustion products from the coke, rising up through the coke bed, transfer heat to the incoming waste feedstock and bring its temperature to gasification conditions.

In addition to the coke, limestone or sandstone may be added as flux additives (to modify the melting point of the mix of inorganic residues) in quantities up to 10% by volume of the feed, depending on the ash chemistry. These flux additives adjust the base/acid ratio of the ultimate slag to levels that are optimal for slag fluidity at the desired discharge temperature. All additives are added commingled with the waste feed.

Oxygen and/or oxygen-enriched air are injected into the middle of the coke bed through primary inlets. Atmospheric air can also be used as the oxidant but the diluent nitrogen decreases the heat content of the product gas and reduces the flame temperature.

The oxidant gas increases the heat release within the coke bed and also transfers heat to the pyrolyzing mass. Temperatures in the middle of the coke bed zone exceed 3000 °C.

Oxygen and/or air are also added above the coke bed and into the feedstock bulk through secondary and tertiary inlets. The ultimate gas temperature leaving the top of the bed is about 1650 °C.

As the gases rise in the chamber, they pass counter-current to the flow of incoming feed. Heat is exchanged to dry and begin the (endothermic) pyrolysis reactions so that the final product gas temperature is between 900 °C and 1000 °C.

Energy recovery

The synthesis gas exiting the PGVR is burned in a combustor at the entrance of an adjacent boiler, where the hot flue gases generate steam for power generation in a steam turbine. Exhaust flue gases are sent through an Air Pollution Control (APC) system comprised of a caustic scrubber to remove acid gases and activated carbon filters before being sent to the stack.

Process byproduct recovery

Inorganic components of the feed waste, the coke, and the fluidizing agent are fused within the coke bed and percolate down through the bed to a slag pool and slag tap at the bottom of the gasifier chamber.

Depending on the quantity of slag, the pool is tapped either periodically or continuously. The molten slag is subjected to a water spray and falls into a quench tank, where it is withdrawn using a drag chain conveyor. The resulting vitrified residue has very limited solubility and has found use in Japan as an aggregate or other 'clean fill' material.

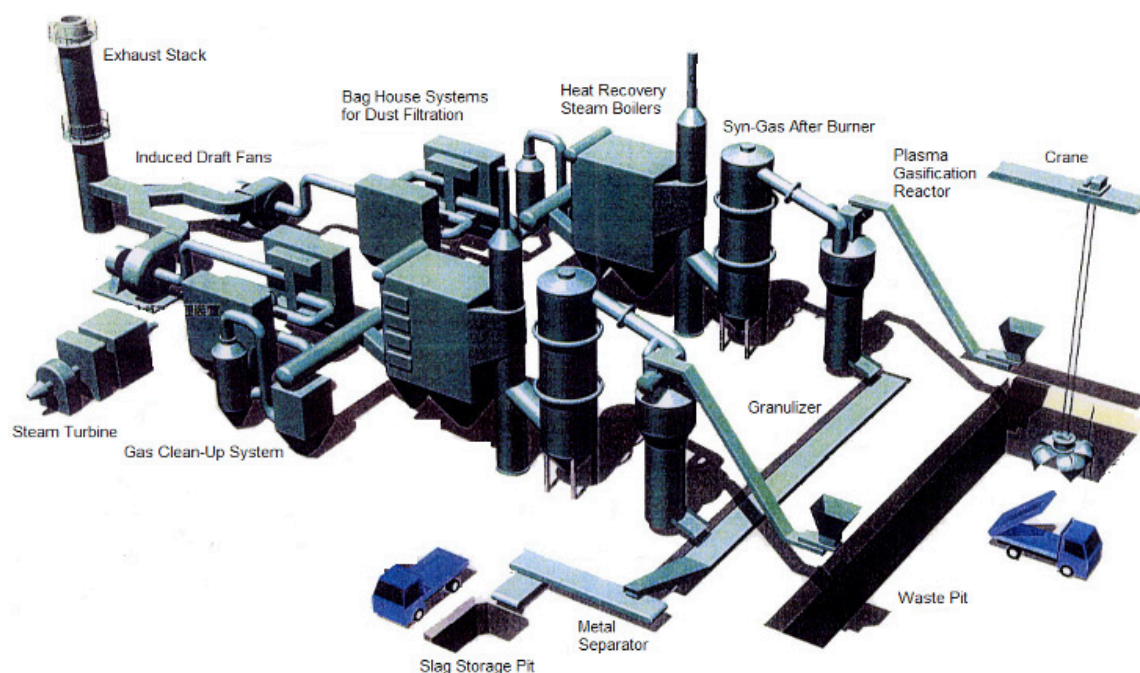
Reference facilities

Utashinai, Japan

The Utashinai EcoValley facility is located in a rural area on the island of Hokkaido. The facility is jointly owned by Hitachi Metals, Hitachi Limited, Hokkaido Prefecture, and the City of Utashinai.

The commercial operation date was April 2003, following a series of operational issues (see below), the EcoValley consortium has decided to cease operation of the facility in 2013. The layout of the Utashinai EcoValley facility is represented in the schematic below.

Figure 79. Layout schematic of the Utashinai EcoValley facility, Japan.



The plant was the first plasma gasification facility designed to operate on a flexible feedstock, varying from 100% MSW to 67% MSW and 33% automotive shredder residue (ASR), depending on the deliveries of the two waste streams to the site.

The plant features two lines for a total throughput rating of 220 tpd for 100% MSW operation. When the plant operates with the higher energy content mixed waste feedstock, the thermal capacity of the plant limits the throughput rating to 150 tpd.

Each of the two gasifiers is powered with four MARC-3 plasma torches, with overall power requirements for plasma torches operation varying thus between 320 and 1200 kW.

Energy recovery

The raw synthesis gas from the gasifiers is burned without conditioning in adjacent boilers for steam generation ahead of a 7.9 MW_e steam turbine generator. The net export of electricity from the facility, when operated at capacity on a 50/50 MSW and ASR feedstock, is 1.5 MW_e (Willis et al. 2010).

²⁷ Adapted from (Willis et al. 2010)

Cost

The original cost of the Utashinai facility was reported by former Westinghouse Plasma licensee GeoPlasma LLC (pre AlterNRG acquisition) at 65 mUSD for construction and 5.5 mUSD for annual O&M costs (URS 2005).

Design flaws and operational issues

The Utashinai facility has been affected by a series of design flaws and ongoing operational issues, requiring re-engineering of major processing equipment, and causing significant downtime.

On the design front, on commissioning Hitachi Metals discovered a serious internal flaw in the dimensions of the internal diameter of the coke bed portion of the reactor. The diameter, originally determined through a direct scale-up of the Yoshi demonstration plant turned out to be too large, causing excessive penetration of gasification air in the coke bed, and limiting the ability of the four plasma torches to properly heat the coke bed. As a result, a number of *cold spots* formed in the coke bed where slag was observed to solidify, with resulting agglomeration of coke and feedstock particles.

An initial solution implemented was to reduce the internal diameter by increasing the thickness of the refractory lining. This approach was particularly attractive as it did not require re-engineering of the reactor vessel. However, the extra thickness of the refractory layer resulted in excessive insulation of the reaction zone, raising the temperature above the melting point of the refractory material, which caused rapid refractory erosion.

Hitachi Metals had to resort ultimately to re-engineer the reactor vessel, decreasing the diameter of the outer steel shell. This issue was only solved after eighteen months of start-up (Willis et al. 2010).

The refractory erosion issues observed through the re-design of the lower 'melting zone' sections of the reactor persisted throughout the early operational life of the plant.

The refractory material initially employed was composed of two layers, an internal high-Alumina (Al_2O_3) layer closest to the coke bed, and an external Silicon Carbide layer. This material was found to have an unacceptably short lifespan, with excessive corrosion observed soon after start-up of the reactor.

After experimenting with a number of refractory layer combinations, Hitachi eventually settled on a solution which is the exact opposite of the original arrangement: high-Alumina on the external 'cold-face' layer and Silicon Carbide on the internal 'hot-face' layer.

This arrangement takes advantage of the high thermal conductivity of Silicon Carbide, allowing a more effective heat transfer to the outer layer of the refractory. In 2010 Hitachi/AlterNRG reported 4 years of successful operation of the new refractory in the melting zone, projecting its useful lifetime to at least 5 years. The refractory layers in the other portion of the reactor has not been changed since start-up, and Hitachi expects its lifetime to exceed 10 years (Willis et al. 2010).

The third and more serious of the commissioning issues experienced at the Utashinai Eco-Valley facility, was excessive particulate carry-over in the syngas stream which caused significant erosion in the afterburner refractory and frequent shutdowns.

The problem was a combination of multiple factors, including:

- the short distance between the feedport entrance in the gasifier and the syngas exit from the reactor,
- the high percentage of fine dust particles and plastics in the ASR feedstock, and
- the high design temperature (1200 °C) for the syngas exiting the gasifier.

At the original design temperature, the particulate was carried over in a molten state, sticking to the refractory in the afterburner. The ash chemistry of the ASR (particularly the plastics components) compounded the problem, with the molten particulate aggressively attacking the refractory layer.

Some design improvements were implemented, extending the length of the feedport pipe inside the reactor, and thus increasing the distance between the feedstock entrance and the syngas exit. This contributed to reduce the amount of particulate carryover but failed to address the refractory erosion issue. Ultimately Hitachi had to resort to lowering the syngas exit temperature to 750 °C to avoid the slag build-up and associated afterburner refractory issues downstream of the gasifier.

Lowering the syngas exit temperature has come at the expense of the efficiency of the facility. The heat recovery steam generator (HRSG), designed to operate at a temperature of 1200 °C is now operating at 900 °C, with resulting lower steam and electricity outputs.

The design flaws and operational issues described have had a substantial impact on the commercial viability of the EcoValley facility. The diameter design and refractory layer arrangements for the lower sections of the gasifier have caused major downtime in the first two years of operation, whereas the particulate carry-over issue was only solved after 5 years of operation, impacting the availability for all these years.

As a result of the extended shutdowns the EcoValley facility failed to process the contracted ASR quantities causing several the companies that were contracted to deliver the ASR to the plant to find disposal alternatives. The EcoValley consortium finds now itself in a situation where it has solved all of the operational issues but cannot source enough feedstock from the local area. As a result the plant is now running at half capacity and is reporting negative financial results.

Hitachi has announced a decision to cease operations at EcoValley in 2013 (Willis et al. 2010).

Brightstar Environmental – SWERF

The *Solid Waste and Energy Recycling Facility* or SWERF, is an integrated waste minimization and energy recovery process based on two-step gasification, or pyro-gasification technology.

The history of the SWERF process and Brightstar Environmental provides an illustrative example of the importance of process modeling and operational experience in waste management technologies, and energy-from-waste (EfW) schemes in particular. Although proven and extensively demonstrated at pre-commercial scale, the SWERF technology failed to achieve performance and operational reliability targets at a full-commercial scale plant based in Wollongong, leading to the decommissioning and dismantling of the facility and resulting in significant financial losses.

Technology development history

The SWERF process was originally developed in the USA by Brightstar Synfuels from the late 1980s and first demonstrated in 1994 at a large particleboard plant. A demonstration unit with a design throughput of 680 kg/h was constructed in 1996 at a facility located near Baton Rouge, Louisiana. This plant was used to test the process on a variety of biomass and organic waste streams.

From 1998 Brightstar Environmental was established as a joint venture between Brightstar Synfuels and Energy Developments Limited (EDL), to further development and commercialization of the process. An ASX-listed independent power producer focused on landfill gas generation, EDL was the majority partner in the Brightstar Environmental joint venture, holding 88% of stock (Williams et al. 2003).

In February 2001, following three years of community consultation and planning activities, a commercial-scale demonstration plant was commissioned at the Kembla Grange site, Wollongong. The plant facility was designed to process 50,000 tonnes per annum (tpa) of unsorted MSW, divert 90% of waste from the White's Gully landfill, and generate up to 5.4 MW_e of electricity.

At the time of the commissioning of the Wollongong facility, BrightStar Environmental marketed aggressively the technology announcing additional projects in Gosnell, Western Australia (27 ktpa initially, then 100 ktpa) and Derby, UK (50,000 tpa) and claiming a pipeline, as of June 2001, of 35 projects and in excess of 9 mtpa of MSW processing capacity (Juniper 2001).

methane content gas stream and introduced into a second gasification stage producing a high hydrogen content synthesis gas with steam as a gasification agent.

The gaseous product streams from the two reactors are blended to obtain a consistent synthesis gas stream optimized for the generator sets, with typical composition reported in the table below.

Table 72. Syngas composition for the SWERF process

| Syngas composition, vol% | | | | | |
|--------------------------|----------------|-----|-----------------|----------------|-------|
| CH ₄ | H ₂ | CO | CO ₂ | N ₂ | Other |
| 30% | 35% | 25% | 9% | <1% | 1% |

SOURCE: (Juniper 2001), Figure E.204, p. E.322

Energy recovery

Energy recovery in the SWERF process was through power generation in four generator sets, based on EDL's series 2000 landfill gas generator sets with modified exhaust, fuel management and detonation control systems. The engines were rated at 1.35 MW_e as for the landfill gas-fueled version.

Operational issues

Despite the commercial-scale of the Wollongong facility, the SWERF was in most regards still a developmental-stage technology. Since commissioning, several design issues in the material handling systems had to be solved before the plant could commence continuous operation.

Material handling issues aside, the Wollongong SWERF plant was affected by ongoing issues with the removal of char from the primary pyrolysis reactor and gasification of char in the secondary gasification reactor.

The original design featured hot char removal from the primary reactor, later abandoned as removal of char at temperatures of 4-500 °C proved problematic, particularly due to risk of auto-ignition of the char materials between the removal and secondary gasification reactor feeding systems.

Brightstar reported development and implementation of an alternative char removal solution, based on wet removal (with char quenching) from as early as mid 2001 (Brightstar Environmental 2002).

Seemingly solving char handling issues, the wet removal system caused even more serious problems in the secondary, char gasification reactor, as the char removed through the wet

systems was not inert and combined with the pyrolysis oils preventing complete carbon conversion and generating difficulties in operating within the performance parameters (energy and material recovery) and emission limits in the facility's EPA licence.

Development of a new secondary gasification reactor became a critical development path for the technology, with Brightstar Environmental reporting by early 2002 of several unsuccessful attempts with alternative design concepts and prototypes tested.

During the extended shut down of the secondary reactor, chars and pyrolysis oils accumulating from the primary reactor became to represent a serious waste management issue, which compounded operational problems with the facility. Following these issues, EDL ceased to fund further development of the facility from late 2002 and tried unsuccessfully to sell its portion of the Brightstar Environmental stock to a third-party buyer.

The total cost of the project at this stage was already 43 mAUD, with 40 mAUD provided by BrightStar Environmental, and the remainder provided by the then Australian Greenhouse Gas Office (AGO) through its 'Technology Showcase' program (2 mAUD), the NSW Sustainable Energy Development Authority (1 mAUD). Following an announcement of ceased operation in March 2004, Wollongong City Council had spent an additional 1.5 mAUD to convert the site in a material recovery facility (MRF) and waste transfer station.

Reported losses by investors associated with the SWERF facility, including from stranded assets and loss of value in the EDL stock, were reported to be between 120 and 140 mAUD.

EDL continues to operate as a developer and operator of landfill gas generation systems and compressed and liquefied natural gas (CNG/LNG) infrastructure.

Ebara – TwinRec

Ebara is an international engineering company specializing in fluid/machinery systems, precision machinery, and environmental engineering. The firm has successfully developed and implemented over 100 waste processing plants, including both incinerators and gasifiers based on a proprietary fluidized bed design.

The Ebara TwinRec process is a fully commercial process that combines fluidized bed gasification with an ash melting furnace.

Technology development and commercialization

The Ebara TwinRec gasification technology, was first developed in the early 1990s as an evolution of their incinerator design based on an integrated boiler fluidized bed (ICFB), and piloted at two demonstration facilities in Japan: Sodegaura, Japan (1x7 tpd unit) started in 1995 and decommissioned in 1997; and Fujisawa, Japan (1x24 tpd unit) started in 1997 and decommissioned in 2001.

Both facilities were subject to extensive tests to support development of operational experience on a range of feedstocks including municipal solid wastes (MSW), refuse derived fuels (RDF), plastics and automotive shredder residues (ASR). The Fujisawa plant was successfully operated on a single 100-days continuous test run between September and December 1997 (Ebara 2007).

Commercial operation started in 2000 with the commissioning of the Aomori plant, followed by ten more commercial facilities, as listed in the Table below.

Table 73. Ebara TwinRec facilities

| Facility | Start-up year | Status | Capacity, tpd | Feedstock | Syngas use |
|------------------------------|---------------|-------------|---------------|---------------------------------|------------|
| Sodegaura pilot plant, Japan | 1995 | shut down | 95 | MSW, RDF, plastic, ASR | ST |
| Fujisawa pilot plant, Japan | 1997 | shut down | 95 | MSW, RDF, plastic, ASR | ST |
| Aomori, Japan | 2000 | operational | 2 x 225 | ASR, sewage sludge | ST |
| Joetsu, Japan | 2000 | operational | 15.7 | Dry sludge, plastics | ST |
| Kurobe, Japan | 2000 | operational | 63 | ASR, plastics, industrial waste | F |
| Sakata, Japan | 2002 | operational | 2 x 98 | MSW | ST |
| Kawaguchi, Japan | 2002 | operational | 3 x 140 | MSW | ST |
| Ube City, Japan | 2002 | operational | 3 x 66 | MSW | ST |
| Seki, Japan | 2003 | operational | 3 x 56 | MSW | ST |
| Iida, Japan | 2003 | operational | 2 x 46.5 | MSW | ST |
| Nagareyama, Japan | 2004 | operational | 3 x 69 | MSW | ST |
| Tokyo Rinki, Japan | 2006 | operational | 2 x 275 | Industrial waste | ST |
| Hino City, Japan | 2007 | operational | 3 x 60 | MSW | ST |

SOURCE: (Ebara 2007)

Notes: ASR - automatic shredder residues; CCGT - combined cycle gas turbine; GE - gas engine;

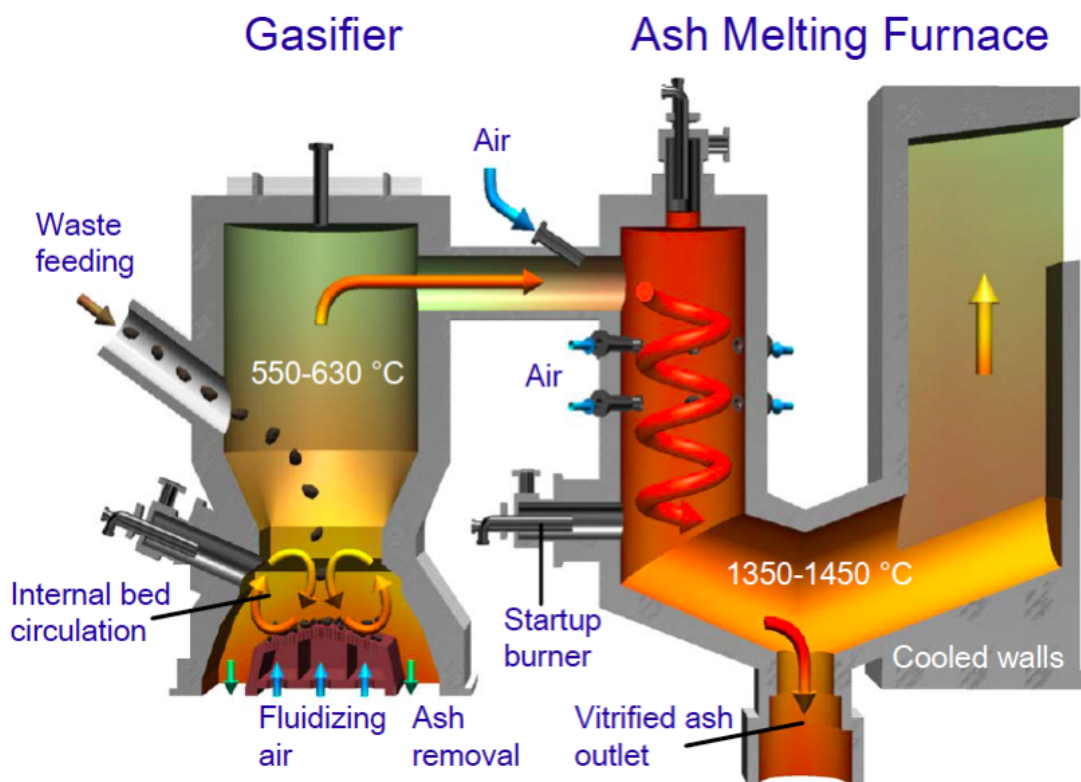
F - direct fuel user; MSW - municipal solid waste; RDF - refuse derived fuel; ST - steam turbine.

The eleven commercial plants currently operated in Japan collectively process 1462 tons of MSW, 1063 tons of industrial waste and 16 tons of sewage sludge per day, for a total installed thermal capacity of 371 MW_{th}.

Process description

The TwinRec process combines a fluidized-bed gasifier, operating at 550-600 °C and atmospheric pressure, with a secondary combustion and ash-melting furnace. The process is summarized in the schematic below.

Figure 81. Schematic representation of the Ebara TwinRec process²⁹



Pre-processing

The TwinRec process accepts a wide range of feedstocks, and has been demonstrated using a variety of waste materials to include automobile shredder residues (ASR), waste plastics, electronics waste and other industrial residues, MSW, and sewage sludge. Minimal pre-processing is required, with solid feedstock materials to be shredded to a maximum particle size of ~30 cm.

²⁹ Adapted from (Selinger & Steiner 2004).

Heating and conversion

In the TwinRec process, heating of the feed materials to gasification conditions (typically 580 °C) is performed through circulation of hot gases in a fluidized bed reactor.

The reactor is based on the company's proprietary revolving or Twin Interchanging Fluidised Bed (TIF), a design developed by Ebara to improve the operational and heat transfer characteristics of the bubbling fluidized bed (BFB) designs without the operational complexities of circulating fluidized bed (CFB) designs.

In essence, the TwinRec reactor is a hybrid between a fixed-grate and a bubbling fluidized bed design, whereby the combination of the fluidizing air and the movement and design of the grate effect greater movement, and hence turbulence, of the dense phase bed.

The low gasification temperature and high-turbulence of the bed allow for easy process control and limited gasification air requirements, resulting in a compact design for both the primary gasification chamber and for the energy recovery and air pollution control (APC) systems downstream.

Energy recovery

The effluent from the fluidized bed, a hot raw synthesis gas with a substantial residual heating value, is burned at very high-temperature in a secondary cyclonic combustion chambers designed to improve combustion efficiency separate fine particles entrained in the synthesis gas flow.

The hot gaseous effluents from the combustion of the synthesis gases are typically circulated through a water-wall boiler, generating steam for industrial processes or power generation in steam turbine. Due to the overall low excess air ratio, the steam boiler can be compact, maximising recovery of the energy content of the waste. The overall air ratio is about 30% excess air at the entrance of the boiler, except in the smaller plants where operation at 50–60% excess air may be necessary to assure good mixing.

The table below provides an overview of the energy recovery options implemented at some of the operating Ebara TwinRec facilities. All TwinRec plants integrate steam power generation with the exception of the Kurobe plant, the gases are burned directly to provide heat for melting of copper-containing residues in the industrial waste stream (40% shredding residues, 15% plastics and 45% copper slag and sorbents from the nearby copper refining facility).

Table 74. Overview of energy recovery options for operating Ebara TwinRec facilities.

| Facility | Capacity, tpd | Feedstock | | Energy recovery | | Energy use | |
|------------------|---------------|---------------|------------|-----------------|----------------------------|------------------------------|---------------|
| | | Components | LHV, MJ/kg | Units | Capacity, MW _{th} | Power, MW _e | Steam, t/h |
| Aomori, Japan | 450 | ASR, sludge | 14.3 | 2 | 40 | 17 | |
| Kurobe, Japan | 63 | ASR, plastics | 10.2 | 2 | 7.4 | direct use (copper smelting) | |
| Sakata, Japan | 196 | MSW | 10.9 | 2 | 12.3 | 2 | |
| Kawaguchi, Japan | 420 | MSW | 13 | 3 | 21 | 12 | 35 |
| Ube City, Japan | 198 | MSW | 12.5 | 3 | 9.5 | 4 | |
| Seki, Japan | 168 | MSW | 11.3 | 3 | 7.3 | 2 | |
| Iida, Japan | 93 | MSW | 8.4 | 2 | 4.5 | 0.78 | not specified |

SOURCES: (Ebara 2007), plant sheets available on Ebara website.

Process by-product recovery

Recyclable metals

The revolving fluidised bed design has the advantage of allowing for easy and effective separation of metallic residues in the waste stream.

Steel, aluminum, copper and iron are easily recovered thanks to the specific combination of low-gasification temperature, moving bed and large particle sizes in the TwinRec design.

The metal in the waste is not burned, melted, or sintered in the first stage of the process, and can be recovered directly from the bottom off-stream of the primary gasification furnace.

Mineral dust and metal oxide powder are vitrified into the glass granulate and can be separated and recycled afterward.

Vitrified slag

In the cyclonic ash-melting furnace, addition of secondary air to the raw synthesis gases brings the temperature to 1350-1450 °C.

The tars, fine char, and ash residue entrained in the gas stream are melted in the furnace and accumulate on the walls of the furnace, where they are vitrified and drained slowly down to the lower section of the furnace, where they are discharged and quenched in a water bath to form a granulate.

The recovered material is compatible national environmental leaching standards for acceptability for recycling in construction in Germany, Japan, and the Netherlands. In Japan, granulate is used as a filler in asphalt.

Reference facilities

Aomori, Japan

The first of the commercial TwinRec facilities, the Aomori Plant owned by the Aomori Renewable Energy Recycling Corporation a joint venture between Seinan and Ebara, started in February 2000.

Figure 82. TwinRec facility in Aomori, Japan



The plant features two 225 tpd TwinRec units and operates on a mix of automotive and brown/white goods shredder residue and mechanically dewatered sewage sludge in amounts from 0% to 30% (by weight) of the shredder residues amounts.

The ASR materials, delivered from five shredder plants and from two non-ferrous material separation plants, meet the requirements of 30 cm top size, and therefore are fed directly to the gasifier without further treatment. Other waste plastic materials and bone meal (in 1000 ton quantities) are treated as available, and a feeding system for boxed, hospital wastes was added.

The plant has an overall thermal capacity of $2 \times 40 \text{ MW}_{\text{th}}$ and 17 MW_{e} of generation capacity.

Materials recovered at the Aomori plant include Ferrous metals (Fe, steel), non-ferrous metals (Al, Cu) from the gasification reactor bottom ash, glass granulates and molten metals in the vitrified flyash (Zn, Pb, Cu).

Kawaguchi City, Japan

The Kawaguchi plant in Japan, is the largest of the Ebara TwinRec installations to operate on 100% MSW, was started in 2002. The facility is operated by Kawaguchi City as the Asahi Environmental Centre.

Figure 83. TwinRec facility in Kawaguchi, Japan



The three processing lines at Kawaguchi process each 140 tpd of mixed MSW including bulky waste with screening and shredding to achieve the maximum particle size of 30 cm. In addition, the plant has the ability to accept up to 27 tpd of bottom ash from the Totsuka Clean Centre, a pre-existing incineration facility in the City.

Energy recovery

The total thermal capacity of the plant is 63 MW_{th}, each of the processing lines generates 25.8 t/h of steam at 3.95 MPa and 400°C. A portion of the steam, at the rate of 35 t/h is delivered as process steam to a recycling facility and a public bath located in proximity of the plant. The remaining steam is used to generate power in a 12 MW_e steam turbine.

Byproduct recovery

The rate of byproduct recovery from the Kawaguchi plant is:

- 10 kg recyclable metals per metric ton MSW processed (ferrous and aluminum);
- 95 kg of vitrified ash (aggregate) per metric ton MSW processed;
- 20 kg inert materials per metric ton MSW processed; and
- 25 kg APC residues per metric ton MSW processed.

The vitrified slag recovered from the three Kawaguchi units was tested for leaching properties according to the stringent Japanese standards in November 2002, the results are reported below.

Table 75. Kawaguchi facility – leachate test results, November 2002

| Units ^a | Facility | | | | |
|--------------------------------|--------------|--------------|--------------|------------|-------|
| | Kawaguchi #1 | Kawaguchi #2 | Kawaguchi #3 | Op. permit | |
| Slag concentrations | | | | | |
| Cd | mg/kg | <0.5 | <0.5 | <0.5 | 9 |
| Pb | mg/kg | 213 | 150 | 273 | 600 |
| As | mg/kg | <0.5 | 0.5 | <0.5 | 50 |
| Total Hg | mg/kg | <0.005 | <0.005 | <0.005 | 3 |
| Leachate concentrations | | | | | |
| Cd | mg/l | <0.001 | <0.001 | <0.001 | 0.01 |
| Pb | mg/l | 0.006 | 0.002 | 0.001 | 0.01 |
| Cr ⁶⁺ | mg/l | 8.3 | 0.7 | 13 | 0.05 |
| As | mg/l | <0.001 | <0.001 | <0.001 | 0.01 |
| Total Hg | mg/l | <0.0005 | <0.0005 | <0.0005 | 0.005 |
| Se | mg/l | <0.001 | <0.001 | <0.001 | 0.01 |

^a concentrations measured at 12% oxygen

Sources: (Selinger and Steiner 2004), Table 1.

Emissions

The air pollution control system at the Kawaguchi plant includes a bag filter, a wet scrubber, and a catalytic catalyst reactor (fed with ammonia) for NO_x control. The height of the stack is 100 m.

Performance test measurements conducted in November 2002 confirmed the plant's ability to operate within operating permit limits, including dioxin emissions below the limit of 50 pg_{I-TEQ}/Nm³. The results of the tests are reported below:

Table 76. Kawaguchi facility – air emission test results, November 2002.

| Units ^a | Facility | | | | |
|--------------------|--------------------------------------|--------------|--------------|------------|------|
| | Kawaguchi #1 | Kawaguchi #2 | Kawaguchi #3 | Op. permit | |
| Particulate | g/Nm ³ | <0.001 | <0.001 | <0.001 | 0.01 |
| HCl | ppm | <1 | <1 | <1 | 10 |
| NO _x | ppm | 21 | 32 | 36 | 50 |
| SO _x | ppm | <1 | <1 | <1 | 10 |
| CO | ppm | 2 | 3 | 2 | 10 |
| Dioxins | pg _{I-TEQ} /Nm ³ | 8.3 | 0.7 | 13 | 50 |
| Total Hg | mg/Nm ³ | <0.005 | <0.005 | <0.005 | n/a |

Sources: (Selinger and Steiner 2004), Table 1.

Waste diversion from landfill

Implementation of the Asahi Clean Centre has allowed Kawaguchi to achieve high rates of diversion from landfill. The gasification facility and the pre-existing Totsuka Clean Centre incineration facility together process the total of MSW generated within Kawaguchi City and the adjacent Hatogaya City.

Specific features of the Asahi Clean Centre, such as co-vitrification of bottom ash from the Totsuka facility and the recirculation of solidified fly ash in the gasification reactor allow the Kawaguchi plant to achieve a diversion rate of 97% (Selinger & Steiner 2004).

Cost

No cost information specific to the Kawaguchi or Aomori facilities is available in the literature. As a term of comparison, a proposal for a 40 tpd TwinRec facility submitted Ebara in 2005 had a construction cost estimate ranging between 14 and 21 mUSD, or 350-670,000 USD/tpd (URS 2005).

IES – Advanced Pyrolytic System

The Advanced Pyrolytic System is a proven, commercial-scale, energy-from-waste (EfW) technology developed by International Environmental Solutions (IES) in California.

Technology development and commercialization

IES commenced development of the APS in 2000, when it received a permit to operate and construct a 41 tpd pilot plant in Romoland, California (Riverside County). The plant was started in the January 2005.

The plant has provided IES with a platform for extensive testing and further development of the APS process, the 40 tpd facility - one third the capacity of the fully commercial 115 tpd module - has operated successfully for four years on a variety of feedstocks, accumulating process data for over 5000 h of operations.

The facility was successfully tested for emissions against the stringent South Coast Air Quality Management District (SCAQMD) standards in 2005 and 2006.

Experience with the Romoland facility has allowed the development of a number of improvements to the process, including the design of a new char residue conveyor, the integration of an intermediate hot gas cyclone separator for flue gases directed to the heat recovery boilers, and the implementation of a flue gas recirculation system for more effective control of NO_x emissions.

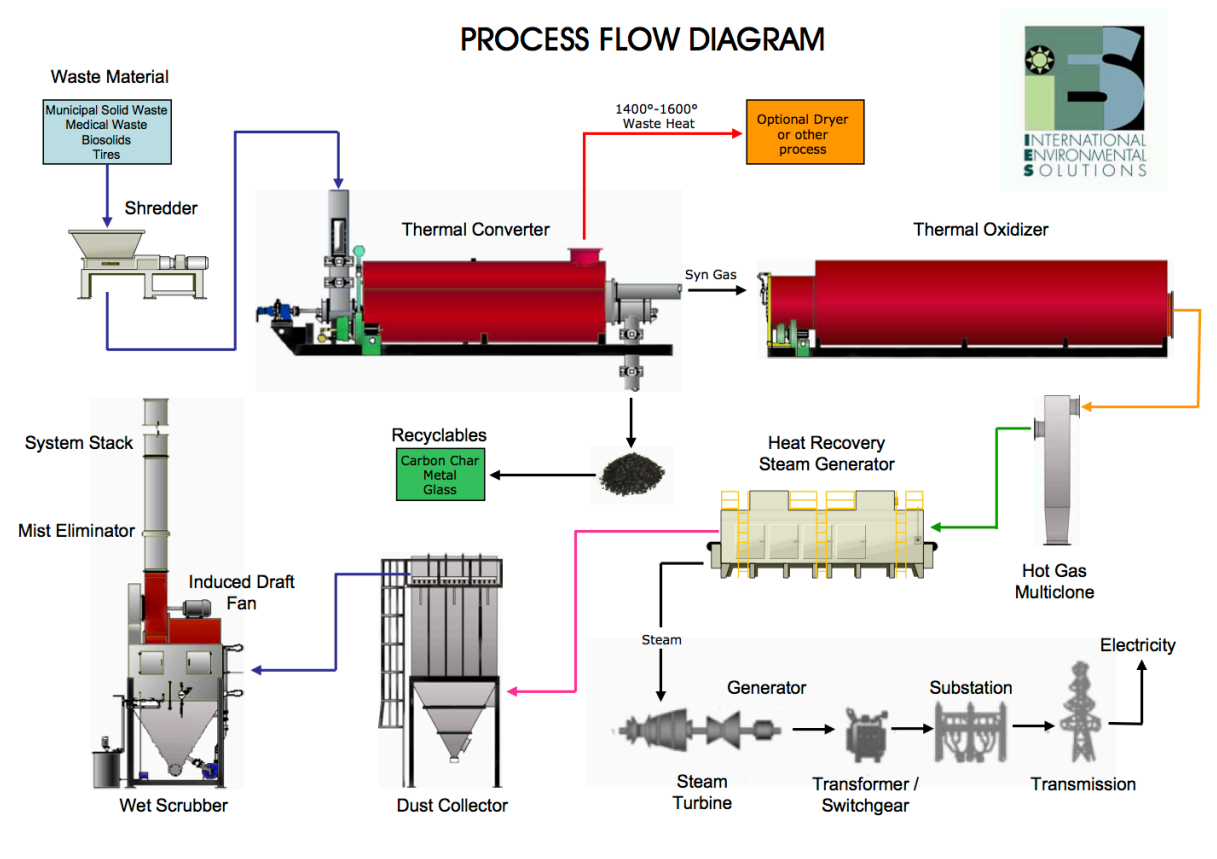
A new demonstration 8tpd unit incorporating all the new designs has been installed at the Technikon Renewable Energy Test Center (RETC) in McLellan California. Start-up for the new demonstration plant was in early 2011, with extensive testing being conducted on a variety of feedstocks.

The Romoland plant has been sold in 2009 and relocated at the Green Gas LLC Mecca facility, in California where it was started-up in December 2010 and will start full commercial operation on tires and MSW from late 2011. The Mecca facility integrates some of the feature of the new designs, namely the carbon discharge conveyor. An expansion of waste processing on the site is planned with the development of a new 125 tpd facility.

Process description

The APS consists of a pyrolysis chamber (the *thermal converter*) followed by a two-stage combustion chamber (the *thermal oxidizer*) and air pollution control (APC) sections, an overview of the APS process is provided in the diagram below.

Figure 84. IES Advanced Pyrolytic System – process schematic



Pre-processing

The APS accepts post-MRF (material recovery facility, for separation of any recyclables) feedstocks requiring minimal pre-processing, i.e. shredding to a maximum top size of 5 cm, then drying to 20 wt% moisture content.

Heating and conversion

Thermal converter

The pre-processed material is fed to the chamber through a screw conveyor. Air locks are utilized at each end of the chamber to maintain a low-oxygen environment and minimize fugitive emissions.

The retort is comprised of a refractory-lined cylindrical shell coaxially surrounding a three-arch, triangular retort, maintained at temperatures in the 760-980 °C range through external heating with a syngas flame (natural gas during start-up).

The two bottom retort arches include specially designed, hydraulically-driven auger screw assemblies that rotate inside the horizontal retort chamber to mix, enhance heat transfer, and translate the waste and residual matter through the retort as pyrolysis occurs. The third, top arch section of the retort serves instead as a conduit through which pyrolysis

gases are drawn off for cleaning, use and subsequent exhaust to the atmosphere, or diversion for external heating in the pyrolyzer. Ash and char exit the chamber through a lock hopper into a collection bin.

Thermal oxidiser

The pyrolysis gases leaving the third section of the retort are ducted to the thermal oxidizer, an insulated, horizontal, two-stage, cylindrical chamber equipped with a 0.5 GJ/h gas burner, where they burn at a flame temperature of 1100 °C.

Combustion air in the thermal oxidiser is supplied in two stages, the first stage runs with slightly less than stoichiometric air, while the second stage runs with an excess of air. This staged process minimizes flame impingement in the thermal reactor.

Combustion gases from the first stage of the thermal oxidiser are conveyed through to the radiant heat zone of the pyrolysis chamber, whereas second stage combustion gases are conveyed to the energy recovery section downstream.

Energy and by-product recovery

The hot, exhaust gases from the thermal oxidizer are first passed through a hot-gas cyclonic separator (for removal of particulates) and further drawn through a heat-recovery steam generator (HRSG), where they raise steam for direct use or for power generation. In a full steam-cycle power generation configurations, the IES system delivers 1.06 MWh_e of electricity (net) per tonne of post-MRF waste processed.

By-products from the APS, when operated on post-MRF waste include:

- Char, 2% (by mass) of waste input,
- Metals, 1.5% (by mass) of waste input, and
- Glass, 10% (by mass) of waste input.

Char and metals can be recovered, achieving a waste diversion rate of 90%.

Air pollution control

The APS does not feature syngas clean-up stages upstream of the thermal oxidizer, as a result, the resulting air pollution control (APC) duty, in terms of the flowrate of exhaust gases to clean-up, is not unlike that of a conventional incinerator.

The air pollution control system consists of selective non-catalytic reduction unit for NO_x control, a baghouse for particulate matter (PM) control, and a scrubber unit for control of acid gases and volatile metals.

Thermoselect - HTR

The Thermoselect High-Temperature Reactor (HTR) is a fully commercial process combining slow pyrolysis with high-temperature gasification and ash melting.

Developed with a focus on thermal conversion of MSW and commercial and industrial waste in large-scale facilities, the HTR concept is particularly attractive as an advanced waste treatment (AWT) alternative in direct competition with incineration-based waste-to-energy (WTE) schemes.

The Thermoselect HTR process accepts unsorted waste, with minimal or zero feedstock preparation/preprocessing and integrates an extensive array of material recovery steps, with the ability to operate close to 100% waste diversion from landfill.

Technology development and commercialization

The HTR process has been developed by Thermoselect SA, a privately-held Swiss company, in the late 1980s, and first demonstrated on a commercial basis at the 95 tonnes per day (tpd) Fondotoce facility, Italy, operated between 1992 and 1999.

Following completion of the Fondotoce demonstration, two client-owned facilities were developed in Chiba, Japan³⁰ (2x150 tpd, start-up in 1999) and Karlsruhe, Germany (3x240 tpd, startup 2000). The operational history of the first two fully commercial Thermoselect plants has been very different. While the Chiba facility was successfully commissioned and still operates to this day, the Karlsruhe facility was plagued by several commissioning problems, and ongoing issues with the air pollution control (APC) system, which led to extended shutdowns of the plant, and ultimately to its decommissioning in 2004. The successful commercial operation of the Chiba plant instead led to 5 further facilities developed in Japan by the JFE. The company website reports development of a large, 5x322 tpd facility, in Caguas, Puerto Rico to commence in 2012.

³⁰ developed under license by JFE Engineering Corporation.

Table 77. Thermostelect facilities

| Facility | Start-up year | Status | Capacity, tpd | Feedstock | Syngas use |
|-------------------------------|---------------|-------------|---------------|----------------------------|------------|
| Fondotoce pilot plant, Italy | 1992 | shut down | 1 x 95 | MSW, industrial waste, ASR | GE |
| Chiba, Japan | 1999 | operational | 2 x 150 | MSW, industrial waste | GE, F |
| Karlsruhe, Germany | 2000 | shut down | 3 x 240 | MSW, industrial waste, ASR | GE |
| Matsu (Shimokita Area), Japan | 2003 | operational | 2 x 70 | MSW | GE |
| Izumi, Japan | 2005 | operational | 1 x 95 | Industrial waste | ST |
| Kurashiki City, Japan | 2005 | operational | 3 x 185 | MSW, industrial waste | F |
| Nagasaki, Japan | 2005 | operational | 3 x 100 | MSW | GE |
| Tokushike Yoshino, Japan | 2005 | operational | 2 x 60 | MSW | GE |
| Yorii, Japan | 2005 | operational | 2 x 225 | Industrial waste | GE, ST |
| Caguas, Puerto Rico | 2012 | proposed | 5 x 322 | MSW | CCGT |

Adapted from: (Niessen 2010), Table 12.23, p.527.

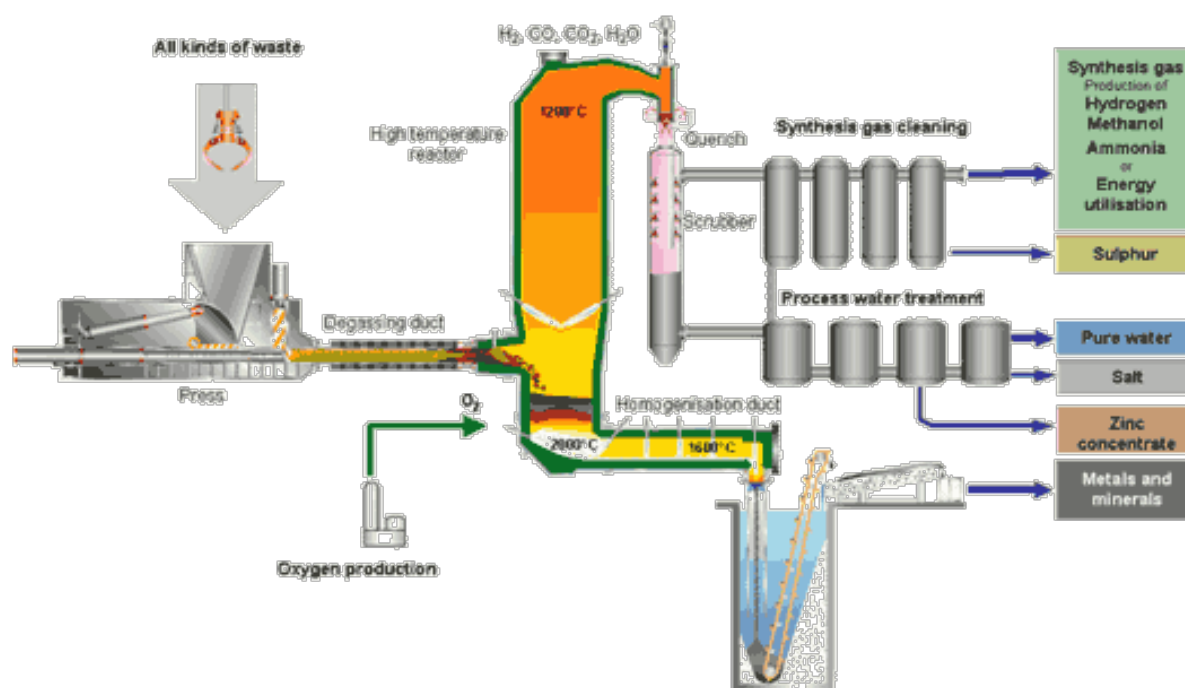
Notes: ASR - automatic shredder residues; CCGT - combined cycle gas turbine; GE - gas engine;

F - direct fuel user; MSW - municipal solid waste; ST - steam turbine.

Process description

The Thermostelect HTR process consists of slow-pyrolysis followed by high-temperature gasification in a fixed-bed oxygen-blown reactor and melting of the inorganic component of the feedstock (ashes, metals, etc.) to form a vitrified slag. The process is summarized in the schematic below.

Figure 85. Schematic representation of the Thermostelect HTR process



³¹ Adapted from materials available in the Thermostelect website: <http://www.thermostelect.com/>

Pre-processing

The Thermoselect technology accepts mixed MSW and industrial waste with no material separation and minimal pre-processing requirements. The raw waste is dropped by grapple from the waste pit into the housing of the compactor, in which the loose material can be pressed against a heavy metal gate. The feedstock is compressed to below 10% of its original volume by means of an industrial scrap metal hydraulic press. The compacted materials are extruded through a gate and fed as a plug of 'fresh' materials to the thermal conversion process downstream.

Heating and conversion

Degassing and pyrolysis

Drying, heating and pyrolysis of the feedstock materials is achieved in a primary chamber, the *degassing channel* where the extruded plug of compacted materials is externally heated by the radiant heat flowing back from the secondary, *high-temperature gasification chamber* (HTC).

The temperature at the end of the degassing channel is maintained at 800° C. As the compacted waste materials are heated they pyrolyse releasing volatile components and steam, from the moisture carried in with the solid waste feedstock. The raw, wet synthesis gas is conveyed from the degassing channel to the upper sections of the HTC which is maintained at 1200 °C.

At this point, the waste plug is much smaller because it has lost its volatile components (water and organic matter). The non-volatile organic portion has been carbonized to a high degree. The inorganic portion of the waste has remained virtually unaffected and is part of the carbon matrix. Upon reaching the transition point with the HTC, the carbon matrix breaks apart and falls into the lower section of the secondary chamber. The travel time through the degassing channel is normally < 2 h.

High-temperature gasification

The matrix of carbon and inorganic material from the degassing channel fills the lower section of the HTC, to form a fixed bed where oxygen is introduced, bringing the local temperature to 2000 °C.

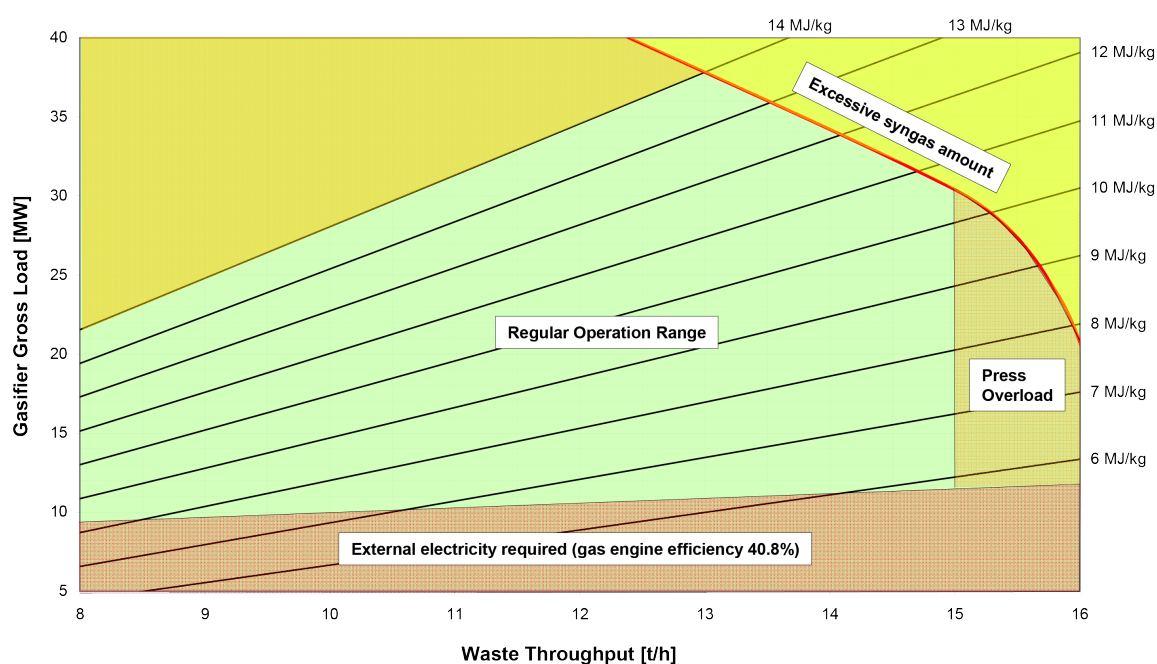
Control of the temperature in this section allows it to effectively perform as a smelter, where the high temperature provides the necessary conditions to melt the inorganic fraction, composed primarily of glass products and various metals that are contained in the carbon matrix.

The inorganic molten mass of mineral and liquid metals flows from the lower section of the HTC into a *homogenization duct*, where it is prepared for removal from the process.

Gases released from the lower sections of the HTC flow upwards to combine with the pyrolysis gases extracted from the degassing channel. The temperature in the upper sections of the HTC is maintained at 1200 °C with the introduction of oxygen, which combined with a residence time approaching 4 s and turbulence is adequate to complete the conversion of the most complex organic compounds and yield a high hydrogen content synthesis gas.

The chart below presents a gasifier firing diagram for a 15 t/h Thermoselect HTC unit. The diagram illustrates the gasifier operating thermal rating (gross) of the gasifier (10-22.5 MW) and resulting operating throughput range (8-15 t/h) as a function of the feedstock heat content.

Figure 86. Gasifier firing diagram for a 15 t/h Thermoselect HTC unit



Gas cooling and cleaning

The resultant synthesis gases exiting the HTC at 1200 °C are immediately cooled down to temperatures below 70 °C by means of water quenching in a spray chamber.

The high volume of water in the quenching step quickly lowers the temperature of the gases and captures particulate matter transported with the gaseous stream, including heavy metals, and water-soluble acid gases such as HCl and HF.

A succession of scrubbers operates the separation of reactor gases from the quench water, including an acid wash at ~60 °C, specialized treatment for H₂S removal, and an alkaline wash at 40 °C.

Residual water vapour is removed by further cooling the gaseous stream down to 5 °C to and passing it through a wet electro-static precipitator (ESP). The gas is warmed to ambient temperature before use.

Synthesis gas quality

The table below reports the typical composition of the cleaned synthesis gas from the Thermoselect process, for a waste feed containing 50% organic matter, 25% inorganic matter and 25% water at 11.9 MJ/kg, for an energy content of the syngas of 8.3 MJ/Nm³.

Table 78. Cleaned reactor gas composition

| Syngas composition, vol% | | | | | |
|--------------------------|----------------|--------|-----------------|----------------|-------|
| CH ₄ | H ₂ | CO | CO ₂ | N ₂ | Other |
| <0.1% | 32-35 | 34-39% | 22-27% | 3-4% | 1% |

SOURCE: (Niessen 2010), Table I2.22, p.527.

Process by-product recovery

One of the key attractiveness of the Thermoselect technology is the extensive array of by-product recovery steps integrated with the process, which combined with minimum pre-processing requirements makes it a particularly well suited solution for EfW applications, with one of the highest waste diversion performances (close to 100%).

Homogenization

The mineral and metal melt flow from the lower sections of the HTC is gravity-fed to an homogenization chamber, where additional oxygen is introduced to react with any remaining carbon particles, bringing the overall oxygen consumption in the Thermoselect plant to ~514 kg per tonne of waste charged, additional heat is also provide to maintain the melt, usually with natural gas or product gas burners at a rate (for natural gas) of 23 kg/ton of waste (Niessen 2010).

A water bath is used to quench the combined molten metal and mineral melt streams. As the temperature drops the vitrified mineral stream forms a mix of granulate, whereas the metal mix freezes, forming metal alloy pellets. The resultant mix of granulates and metal pellets are recovered using a drag chain conveyor.

The glass-like material is suitable for a variety of uses, including aggregates and raw components for construction materials, mineral and insulation fibres and general 'clean-fill' material. Thermoselect is also reported to actively investigate potential markets for the use of the metal residues for metallurgical processes (Niessen 2010).

Sulphur recovery

The sulphur-removal system converts hydrogen sulphide (H_2S) to sulphur using a ferric iron complex. In an adjoining stage, the ferrous iron complex is regenerated using oxygen from air and recycled from the main process, with sulphur precipitated as the element.

The removal of elemental sulphur (S), compared with the removal of sulphur as gypsum ($CaSO_4$) common to most control processes based on the use of lime, reduces the mass of sulphur solids end product by a factor of more than four. Thermoselect indicates the sulphur to be of sale quality.

Water recovery

Thermoselect claims the processing-water solutions generated from the gas-cleaning process to comply with sewerage discharge guidelines. Alternatively, the process water can be subjected to chemical treatment and precipitation to remove heavy metal hydroxides and other insoluble portions as a solid concentrate.

A reverse osmosis membrane step removes the remaining salts (primarily sodium chloride), followed by the evaporation of water to concentrate and remove soluble residuals. The clean, distilled water is returned for use in the process-water loops and cooling towers.

Since the process recovers water contained in the original waste input, there is an excess of water recovered as part of the process, which could be recovered for other uses or sprayed on hybrid cooling towers and evaporated.

Reference facilities

Fondotoce, Italy

The Thermoselect technology operated at an industrial-scale demonstration and pilot plant in Fondotoce, Italy, from 1992 to 1998.

Karlsruhe, Germany

The Karlsruhe facility was commissioned in 2000 by owner/operator EnBW GmBH (previously known as electric utility Badenwerke AG). The process consisted of 3x240 tpd HTR modules fed with a mixture of MSW, industrial waste and automatic shredder waste

(ASW). Synthesis gas from the HTR was used in a gas engine system to generate power for export.

Operational and licensing issues

The Karlsruhe plant has been plagued by commissioning problems, causing delays in licensing and complicated by organizational, permit that led ultimately to the plant decommissioning in 2004.

A failure in the Air Pollution Control system (APC) saw EnBW implement a flare chamber, comprised of ignition burners and a chimney, as an interim solution to safely vent the syngas exiting the high-temperature gasification sections.

However the German EPA intervened to notify that operation of the emergency vent was in breach of the conditions for the operating permit for the plant, requiring an APC to operate at all times.

Faced with the prospect of the risks associated with obtaining a new permit from the EPA with adequate provisions for the emergency vent and the obligation to implement a new air pollution control system for the facility, EnBW opted for the latter implemented after over 18 months of idle time and significant additional investment costs.

Following significant reorganizational changes and an unsuccessful attempt to sue Thermosteel for all costs associated with the flare chamber rework, EnBW have mothballed Karlsruhe in an apparent strategy to bolster its legal position in continuing appeal actions.

The lessons learnt at Karlsruhe point to the importance of adequate and comprehensive permitting conditions – particularly for emergency operations – and of the adoption of redundant air pollution control systems (now an obligation under the European Waste and Large-scale combustion sources Directives), rather than flaws in the fundamental environmental and operational performance of the Thermosteel HTR technology, as demonstrated by the successful implementation of new facilities by clients in Japan and elsewhere.

Cost information

The overall cost of the Karlsruhe facility was reported by US-licensee Interstate Waste technologies (IWT) to be 120 mUSD, with 19 mUSD of annual O&M expenditure (URS 2005).

Chiba City, Japan

In 1997, the former Kawasaki Steel, now JFE, with financial support from the New Energy and Industrial Technology Development Organization (NEDO), Ministry for Energy Trade and Industry (METI), began construction of a 300 tpd facility based on the Thermoselect process.

Commissioning tests

During FY 1999, the plant was operated on a demonstration basis, as part of a joint research project between JFE, Chiba City and the Chiba Prefecture, with the aim to test the technology and develop adequate operational expertise prior to its full commercial operation.

The demonstration test, the first of its kind for a full-scale gasification, reforming and ash melting equipment in Japan, saw the plant treat over 15,000 t of municipal solid waste from the Chiba prefecture over a period of 130 days, with the single longest continuous run exceeding 93 days, leading to the full certification of the plant.

Cost information

The overall cost of the Chiba facility was reported by US-licensee Interstate Waste technologies (IWT) to be 80 mUSD, with 13 mUSD of annual O&M expenditure (URS 2005).

TPS – Termiska AB

The Termiska AB is a low-pressure, air-blown circulating fluidized bed (CFB) gasification technology developed specialized process engineering firm TPS, headquartered in Nyköping, Sweden.

The technology is fully proven, with one commercial-scale demonstration facility operating from 1993 in Italy. However, subsequent high-profile commercialization initiatives focused on biomass feedstocks have fallen through at the commissioning stages, with little information available on a pipeline of future projects.

Technology development and commercialization

TPS began development of circulating fluidized bed (CFB) boilers in the late 1970s. In the mid 1980s company embarked in the development of circulating fluidized bed gasifiers, and constructed a constructed a 2 MW_{th} biomass-fuelled atmospheric gasification system pilot plant in 1984.

The pilot plant operated successfully on a range of feedstocks and provided a wealth of process data for scale-up facilities. In 1988 a gas clean-up system was later added to the plant In 1988 the pilot plant was retrofitted with a gas clean-up system comprised of a dolomite tar cracker, cold gas filter and wet scrubber, and a 500 kW_e modified diesel engine for power generation.

In 1988, Termiska Processer AB (TPS) licensed their low-pressure, air-blown, circulating fluidized bed (CFB) gasification process to Ansaldo Aerimpianti SpA, of Italy. In 1992 Ansaldo installed a commercial, two-bed unit in Grève-in-Chianti, Italy. The two units with a combined thermal capacity of 30 MW_{th} are fed on a pelletized RDF fuel from MSW, with seasonal additions of shredded woodwaste and agricultural wastes.

The Greve-in-Chianti remains a successful demonstration of the CFB concept developed by TPS, operated flawlessly throughout the life of the facility, a number of issues with the energy recovery sections however required significant additional investment during the early operational life of the plant (1993-97).

Following successful demonstration at Greve-in-Chianti, the Termiska AB concept was selected for two high-profile biomass gasification projects: the EU-funded 8 MW_e ARBRE biomass integrated gasification combined cycle (BIGCC) project in the UK and the Biomass Integrated Gasification Gas Turbine (BIG-GT) project in Brazil, funded under the World Bank's Global Environment Facility (GEF) program.

Both projects provided unvaluable operational experience in the development of syngas-fuelled gas turbines, but were stalled at the advanced commissioning stages due to a combination of technical and organizational issues. . No further commercialization of the TPS technology has been reported to date.

Process description

Pre-processing

RDF preparation

The refuse derived fuel (RDF) for the TPS process is prepared through primary shredding of the MSW feedstock in an horizontal shaft hammermill or shear shredder, secondary shredding in an hammermill, followed by magnetic separation for removal of magnetic metals, and disc screening of fines for removal of glass and grit.

Pelletization of the RDF is optional and was implemented at the Greve in Chianti facility, to reduce hauling expenses. It is common to incorporate some kind of intermediate RDF storage as a buffer between RDF preparation and the combustion facility. At the Greve facility, four 80 ton steel silos were used. The RDF feed specifications for the Greve system are the following:

Table 79. TPS/Ansaldo Greve in Chianti facility, RDF specifications

| | |
|---------------------------------|----------|
| Dimensions | |
| Diameter, mm | 0-15 |
| Length, mm | 50-150 |
| Bulk density, kg/m ³ | 500-700 |
| Proximate analysis | |
| Lower Heating Value, MJ/kg | 17.2 |
| Moisture (typical) | 6.5% |
| Volatile matter | 71.1% |
| Fixed carbon | 11.4% |
| Sulphur | 0.5% |
| Chlorine | 0.4-0.6% |
| Total non-combustibles | 11% |

SOURCE: (Niessen 2010), p.512.

RDF reclaiming and feeding

In the TPS concept, a twin-screw reclaimer 'digs' the RDF from the intermediate storage silos and deposits into a bucket conveyor, from where it is moved through a screw conveyor and discharged in the feed hopper. Another twin-screw reclaimer is used to extract RDF from the hopper, passed through a rotary valve and chuted into the gasifier.

Fluid bed gasifier

The heart of the TPS process is the fluidized bed gasifier: a cylindrical, bubbling bed system, operating at about atmospheric pressure at the top of the bed.

In the lower 'dense bed', with temperatures of ~700-800 °C, the RDF feed is maintained for a relatively long residence time, till it volatilizes- As particles are reduced, they are lifted out of the dense bubbling bed zone.

Addition of steam to the dense bed facilitates gasification of carbon in wastes with high fixed carbon content. Secondary air is injected above the dense bed zone.

The combined effects of increased mass flow, and heat release (through further oxidation) resulting from secondary air injection, contribute to increase the upward gas velocity and facilitating carbon oxidation. In this zone, temperatures reach higher zones, referred to by TPS as 'fast bed' increases to about 850-950 °C.

In beds firing low-moisture content feedstocks, secondary steam injection to the fluidizing gas flow is necessary to promote gasification of carbon to CO and H₂.

The gases leaving the bed are passes through a duct incorporating U-beam interceptor for the removal of particulate. A large-diameter, refractory-lined cyclone chamber follows where additional particulate recovery occurs.

A vertical accumulation pipe is used to collect the solid streams from the U-beam and cyclone hoppers, where they form an air seal or plug. The lower mass of solids at the bottom of the pipe is fluidized through nitrogen injection prior to discharge back in the dense phase of the bed.

Gases leaving the bed pass through a duct incorporating U-beam particulate interception. The gas then passes to a large-diameter, refractory-lined cyclone where additional particulate recovery occurs. Solid streams from the U-beam and cyclone hoppers accumulate in a vertical pipe, where they form an air seal or plug. At the very bottom of the accumulation pipe, a small amount of nitrogen is introduced to fluidize the lower mass of solids. Then, by gravity, the fluidized solids flow from the pipe and are reintroduced into the dense-phase, bubbling fluidized bed.

Nitrogen rather than air as the fluidizing medium to avoid the high temperatures that would result if air (with oxygen) was used to move the still-hot, ignitable char solids.

The gas leaving the cyclone is thus a mixture of synthesis gas, hydrocarbons and tars with some residual particulate matter, all diluted with nitrogen from the air used in the process.

Syngas cleaning and utilization

The raw syngas exiting the TPS reactor can be used directly as a medium heat content fuel in industrial combustors (eg. rotary cement or lightweight aggregate kilns or process furnaces), either alone or in combination with fossil fuel to trim operations for load following.

Use of the fuel in an industrial or utility boiler for steam and/or power production requires implementation of a downstream air pollution control (APC) train to remove HCl, HF, SO₂, Hg and other heavy metals, particulate, and so on, from the flue gases to the extent required by the chemistry of the RDF and regulatory requirements.

Use of the off-gases from the fluid bed in a gas engine or gas turbine requires clean-up. The TPS concept features a hot-gas cleanup system to avoid efficiency penalties associated with the loss of sensible heat of the fuel gas. The hot-gas cleanup system is comprised of the dolomite tar cracker and associated cyclone appended to the gasifier. The cracker achieves nearly complete conversion of tars into lower molecular-weight compounds and trace quantities of benzene, toluene and naphthalene. Hydrogen cyanide and fuel-bound nitrogen decompose into nitrogen gas (N₂) or ammonia (NH₃).

At the higher temperatures of the cracker bed, carbon containing dust is gasified by residual oxidizing gases (H₂O and CO₂) at the higher temperatures of the cracker bed.

Following the cracker, a heat recovery boiler brings the temperature down to about 200 °C, where a fabric filter system removes particulate matter. The particulate consists mainly of calcined dolomite and fine soot and is of nonabrasive nature. At this point, the gas is suitable for use in many fuel-sensitive combustors.

Air pollution control

In addition to the acid gas control achieved through the dolomitic lime addition, the combustion train is normally equipped with fabric filters for particulate capture. The demonstrated sulfur oxides removal is over 70%. Carbon injection can be provided for mercury control, although the Grève data suggest that acceptable mercury emissions may be achievable without this feature. TPS offers a wet scrubber system when there is a need for enhanced ammonia, tar, acid gas (H₂S and HCl), and condensable vapor removal.

At this point, the fuel gas is of a quality that can be burned in a boiler to generate steam (without further cleanup) or further cleaned to be used as fuel in a gas engine or turbine combustor for the generation of electricity.

Reference facilities

Greve in Chianti

The Greve in Chianti plant is equipped with two TPS CFB gasification units, each rated at 15 MW_t and a capacity of 100 tpd of RDF pellets. The beds also have processed biomass (coarsely shredded wood or agricultural wastes). Fuel gas generated at the plant is either burned in a boiler to generate electricity or used as a fuel in an adjacent lime kiln operation.

These gasifiers are used alternately to feed the single boiler. However, produced gas in excess of that required by the boiler (and gas from the second gasifier, when required) is cooled to 400°C but not cleaned, and transported (by pipeline) a short distance to a nearby cement plant, operated by SACCI. Here, the produced gas is used as fuel for the cement kiln. The SACCI plant also uses the ash and spent lime from the Greve plant, in return providing fresh lime for the scrubber.

The typical gas composition from the Grève facility operated on RDF feed is shown below.

Table 80. Typical off-gas composition for the TPS Greve in Chianti facility

| Component | Composition vol% |
|-------------------------------|---------------------|
| CO ₂ | 15.65 |
| N ₂ + Ar | 45.83 |
| CO | 8.79 |
| H ₂ | 8.61 |
| Methane | 6.51 |
| C _x H _y | 4.88 |
| H ₂ S | 48.61 (ppm) |
| H ₂ O | 9.48 |
| Other | 0.14 |
| Total | 100 |
| LHV, MJ/Nm ³ | 7.53 |

SOURCE: (Granatstein 2003).

Cost information

The total investment for the Greve in Chianti facility, inclusive of capital expenditure for redesign of the boiler sections, was 27.8 mEUR (Granatstein 2003).

References

- APC, 2011a. *Kerbside Domestic Waste Audit for City of Sydney*, APC Environmental Management, October 2011.
- APC, 2011b. *Regional Waste Audit Report for SSRoC - results for all participating Councils*, APC Environmental Management, September 2011.
- ASTM D34, 2007. *ASTM D5468-02(2007) Standard Test Method for Gross Calorific and Ash Value of Waste Materials*, Subcommittee D34.03 Waste Management (Treatment, Recovery and Re-use), American Society for Testing of Materials. Available at: <http://www.astm.org/Standards/D5468.htm>.
- Basu, P., 2010. *Biomass Gasification and Pyrolysis*, Burlington, MA: Academic Press.
- Bridgwater, A.V., 2003. *Pyrolysis and Gasification of Biomass and Waste*,
- Brightstar Environmental, 2002. SWERF Technical Presentation. In Whites Gully, NSW, pp. 1–20.
- BTG, 2008. *BTG Biomass Gasification 2008 ed*, BTG biomass technology group BV.
- CDM EB, 2012. *Approved consolidated baseline and monitoring methodology ACM0022 "Alternative waste treatment processes"* 1st ed, Executive Board, Clean Development Mechanism, United Nations Framework Convention on Climate Change.
- Channiwala, S.A. & Parikh, P.P., 2002. A unified correlation for estimating HHV of solid, liquid and gaseous fuels. *Fuel*, 81(8), pp.1051–1063.
- City of Sydney, 2013a. *City of Sydney Decentralised Energy Master Plan - Renewable Energy DRAFT*, City of Sydney. Available at: <http://www.sydney2030.com.au/wp-content/uploads/RENEWABLE-ENERGY-MASTER-PLAN.pdf>.
- City of Sydney, 2013b. *City of Sydney Decentralised Energy Master Plan - Trigeneration FINAL, ADOPTED*, City of Sydney. Available at: <http://www.sydney2030.com.au/wp-content/uploads/Decentralised-Energy-Master-Plan---Trigeneration---Adopted-15MB.pdf>.
- DCCEE, 2012. *National Greenhouse and Energy Reporting System Measurement - Technical Guidelines for the estimation of greenhouse gas emissions by facilities in Australia*, Department of Climate Change and Energy Efficiency, Commonwealth of Australia.
- DECCW, 2010. *Disposal based survey of the commercial and industrial waste stream in Sydney 2010 ed*, Department of Environment, Climate Change and Water, New South Wales Government.
- Ebara, 2007. TwinRec Reference List. pp.1–1.
- Granatstein, D.L., 2003. *CASE STUDY ON WASTE-FUELLED GASIFICATION PROJECT GREVE IN CHIANTI, ITALY*, IEA BIOENERGY AGREEMENT—TASK 36.
- Hyder Consulting, 2011. *Professional Writer for Waste Strategy White Paper -Greenhouse Gas Emissions Model*, Hyder Consulting.

- Hyder Consulting, 2012. *Waste Management Issues for Southern Sydney Councils*, Hyder Consulting.
- Hyder Consulting, 2013. Technical Due Diligence on Entech Gasification Technology - SUMMARY REPORT, Commercial in Confidence, courtesy of New Energy Corporation.
- Juniper, 2009. *Juniper Ratings Report - Gasification* 3rd ed,
- Juniper, 2001. *Pyrolysis & Gasification of Waste - A Worldwide Technology and Business Review* 2nd ed, Juniper Consulting Services, October 2001.
- Kayhanian, M., Tchobanoglous, G. & Brown, R.C., 2007. Biomass Conversion Processes for Energy Recovery. In F. Kreith & D. Y. Goswami, eds. *Handbook of Energy Conservation and Renewable Energy*. Taylor & Francis Group, pp. 25–1–25–68.
- Niessen, W.R., 2010. (Niessen 2010) Combustion & Incineration Processes. pp.1–712.
- Nolan-ITU, 2001. *Guideline for Determining the Renewable Components in Waste for Electricity Generation*, Clean Energy Regulator, Australian Government.
- NSW EPA, 2013. *NSW Energy from Waste. Draft Policy Statement for Public Consultation*, New South Wales Environmental Protection Authority.
- NSW TI, 2012. *New South Wales 2010-2011 Gas Networks Performance Report*, Division of Resources and Energy, NSW Trade & Investment.
- Selinger, A. & Steiner, C., 2004. TWINREC FLUIDIZED BED GASIFICATION AND ASH MELTING – REVIEW OF FOUR YEARS OF COMMERCIAL PLANT OPERATION. In IT3'04 Conference. Phoenix, Arizona, pp. 1–12.
- Taylor, R., Howes, J. & Bauen, A., 2009. *Review of Technologies for Gasification of Biomass and Wastes* FINAL REPORT, NNFCC.
- TWE, 2013. *Renewable Gases Supply Infrastructure* FINAL DRAFT, Sydney, Australia: Talent with Energy. Available at: <http://www.sydney2030.com.au/wp-content/uploads/RENEWABLE-ENERGY-MASTER-PLAN-TECHNICAL-APPENDIX-2-RENEWABLE-GASES-SUPPLY-INFRASTRUCTURE.pdf>.
- URS, 2005. *Conversion Technology Evaluation Report*, Prepared by URS for Department of Public Works, County of Los Angeles, August 2005.
- WA EPA, 2013. *Environmental and health performance of waste to energy technologies*, Environmental Protection Authority, Western Australia Government.
- Williams, R.B., Jenkins, B.M. & Nguyen, D., 2003. *Solid Waste Conversion*, Prepared for Integrated Waste Management Board, California Environmental Protection Agency, December 2003.
- Willis, K.P., Osada, S. & Willerton, K.L., 2010. Plasma Gasification: lessons learned at Eco-Valley WTE facility. In Proceedings of the 18th Annual North American Waste-to-Energy Conference NAWTEC18. Orlando, FL, pp. 1–8.

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