8.0 APPENDIX

Literature Survey of Biomass Gasification Technologies

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1 LITERATURE SURVEY OF BIOMASS GASIFICATION TECHNOLOGIES

1.1 BIOMASS GASIFICATION TECHNOLOGIES

Biomass gasification has a long development history. Numerous systems have been developed and commercialized in the past to supply thermal energy and fuel gas or synthesis gas (syngas) for industrial and transportation applications. Simple gasification systems are still available today that are suitable for developing countries where large quantities of easily accessible biomass are available. These systems are generally low efficiency and produce either heat or electrical power. Advanced systems are needed for western countries for power and combined heat/power generation. Advanced systems provide high efficiencies with reduced emissions to mitigate greenhouse gas emissions. A literature review was conducted to identify and define various gasification systems for heat and/or electrical power generation. Much information was obtained from the internet through company websites, news releases, and various interest groups. The report published by Juniper Consultancy Services Ltd. ("Technology and Business Review: Pyrolysis and Gasification of Waste – A Worldwide Technology and Business Review," Vol. 1 & 2, 2000) was also used extensively. This literature survey summarizes simple systems for heat and/or power generation (that are suitable when efficiency and emissions are not priority factors) and advanced systems for power and combined heat/power generation.

1.1.1 Simple Biomass Gasification Systems

Simple gasification systems produce syngas with a low-heating content at atmospheric or low pressure. The fuel syngas can be used for operating gas engines for small-scale power production. In general, the syngas is not suitable for advanced turbines or chemical production. Over 14 of these simple systems are reviewed.

1.1.1.1 BG Technologies USA, Inc.

BG Technologies USA, Inc., has licensed gasification technology from Ankur Scientific Energy Technologies PVT, LTD., of India for worldwide distribution (www.bgtechnologies.net and www.ankurscientific.com). Ankur Scientific has over 400 installations worldwide using this technology for processing wood chips, palm nut shells, cotton stalks, rice hulls, maize cobs, soy husks, coconut shells, and sawdust. The BG Technologies electric system consists of a biomass gasifier, gas cleaning and cooling equipment, and a diesel generator. The diesel generator is operated under dual fuel mode using diesel and producer gas from the gasifier which reduces diesel consumption by about 70%. The main objective of this system is to displace some of the fuel requirement for the diesel generator. Three systems are offered at 100, 250, and 400 kW_e capacities with conversion efficiencies ranging from 70-75%. The typical composition of the syngas is 19±3% CO, 10±4% CO_2, 50% N_2, 18±2% H_2, and up to 3% of CH_4.

1.1.1.2 BIVKIN Gasification Technology

The Netherlands Energy Research Foundation (ECN) in Petten, Netherlands, developed and built a pilot circulating fluidized bed (CFB) gasification plant using the BIVKIN (BIomassa Vergassings Karakeriserings INstallatie) process in cooperation with Novem, Afvalzorg, and Stork (Van den Broek, et al., 1997). The plant was initially used at the ECN location in Petten for the characterization of more than 15 different biomass species, including wood, sludge, grass, and manure. ECN has been conducting tests to improve the gas quality so that it can be used for electrical generation in a gas engine. The CFB gasifier is integrated with a 500 kW_e internal combustion (IC) engine at the pilot plant. A diagram of the BIVKIN process is shown in Figure 1.

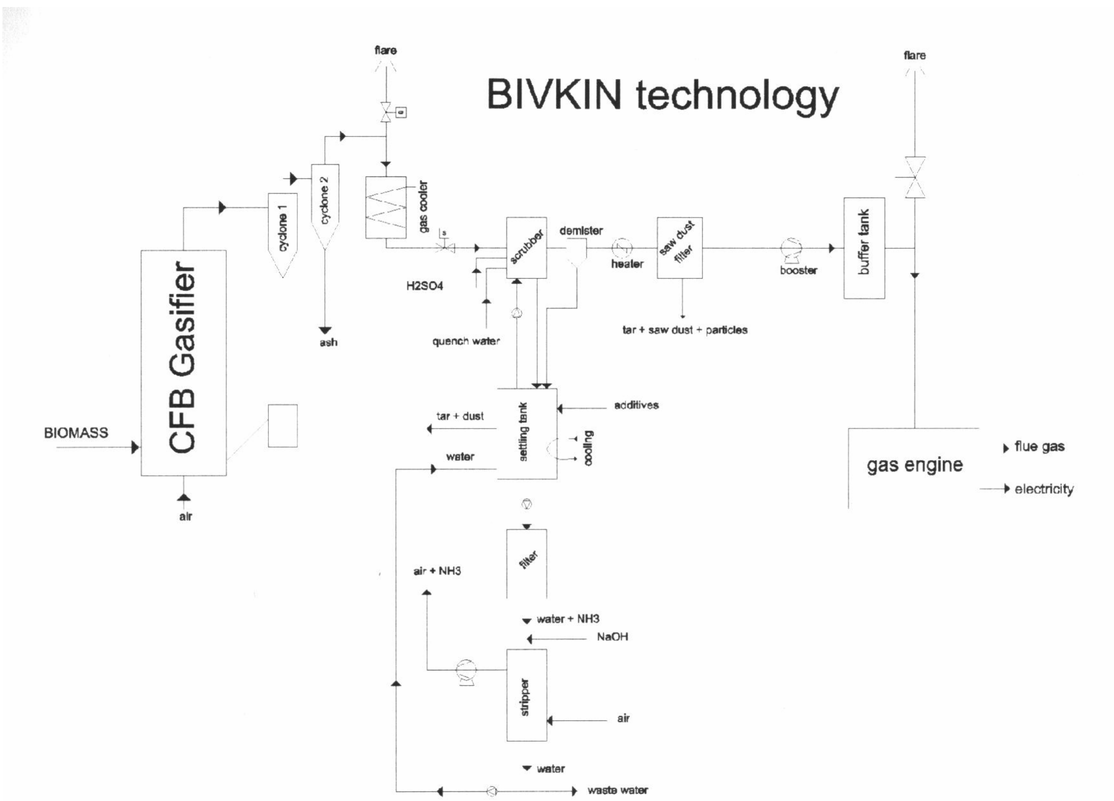

Figure 1. Process Diagram of the BIVKIN Gasification Technology (Van der Drift et al., 2000)

Operation of the pilot plant was initiated in 1996. It had operated for more than 500 hours with various fuels as of August 2000. The operation of the gasifier is very stable, and complete automation of the gasifier is possible. Pictures of the BIVKIN-based gasification plant in Petten, Netherlands, are shown in Figure 2.

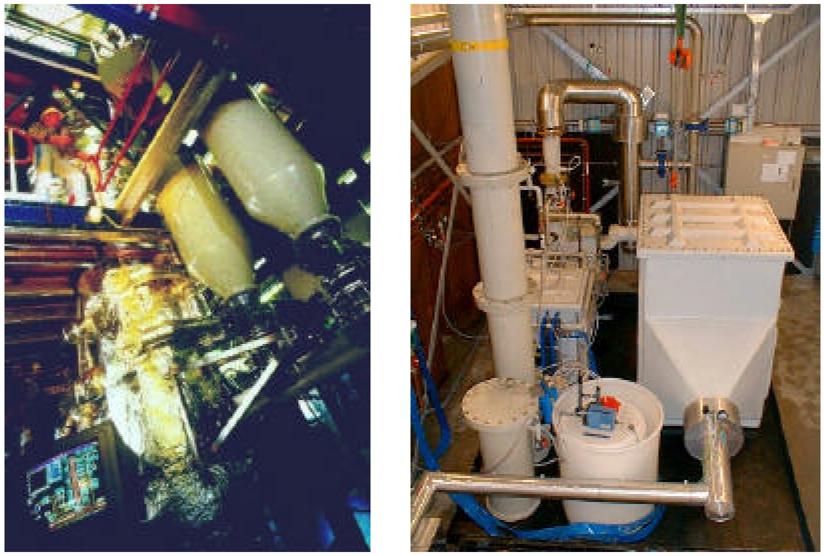

Figure 2. Pictures of the BIVKIN-based Gasification System Pilot Plant (ECN)

ECN, Shell, and HoSt (with co-financing from Novem) performed a study to evaluate the engineering concept and cost for a commercial-scale facility using the BIVKIN technology in the electrical output range of 1 to 5 MW_e. A non-confidential version of the report is available from ECN (Van der Drift et al., 2000). The study evaluated three different sizes with the following scenarios: 5 MW_{th} gasifier with gas engine for electricity production, 12.5 MW_{th} gasifier with gas engine for electricity production, and 14.7 MW_{th} gasifier with gas engine and steam turbine for electricity production. The fuels evaluated were clean biomass at 40% moisture, clean biomass at 10% moisture, and contaminated biomass at 10% moisture. For the wet biomass (40%), the fuel inputs were adjusted to 4.62, 11.55, and 13.58 MW_{th} to compensate for the additional water. A dryer is required to remove the excess water to provide the stated fuel input to the gasifier. The schemes for these are shown in Figure 3 and Figure 4. Costs of items such as engineering, instrumentation, electric equipment, piping, and civil were determined based on detailed calculations for an 8 MW_{th} biomass combustion plant that was actually built in Lelystad, Netherlands. A summary of the investment for these scenarios is shown in Table 1.

Table 1. Investment for BIVKIN-based Gasification Systems

Fuel Input		14.7	12.5	5
Electricity (no heat)				
Net electricity output	MW_e	4.27		
1st Commercial plant investment	M$	13.6		
	$/kW$_e$	3180		
10th Plant investment	M$	12.2		
	$/kW$_e$	2860		
Combined Heat and Power				
Net electricity output	MW_e	4.06	3.20	1.27
Net heat output	MW_{th}	4.17	4.45	1.79
1st Commercial plant investment	M$	13.2	10.2	5.6
	$/kW$_e$	3250	3190	4370
10th Plant investment	M$	11.8	8.9	4.6
	$/kW$_e$	2900	2770	3660

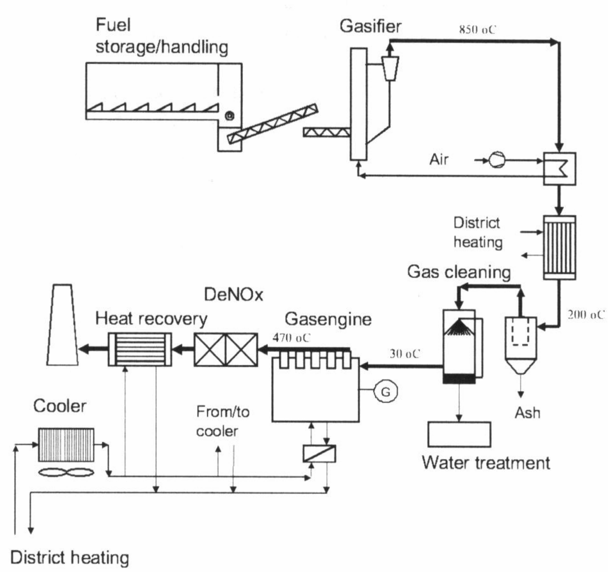

Figure 3. Flow sheet of the 5 and 12.5 MW_{th} BIVKIN-based power plant

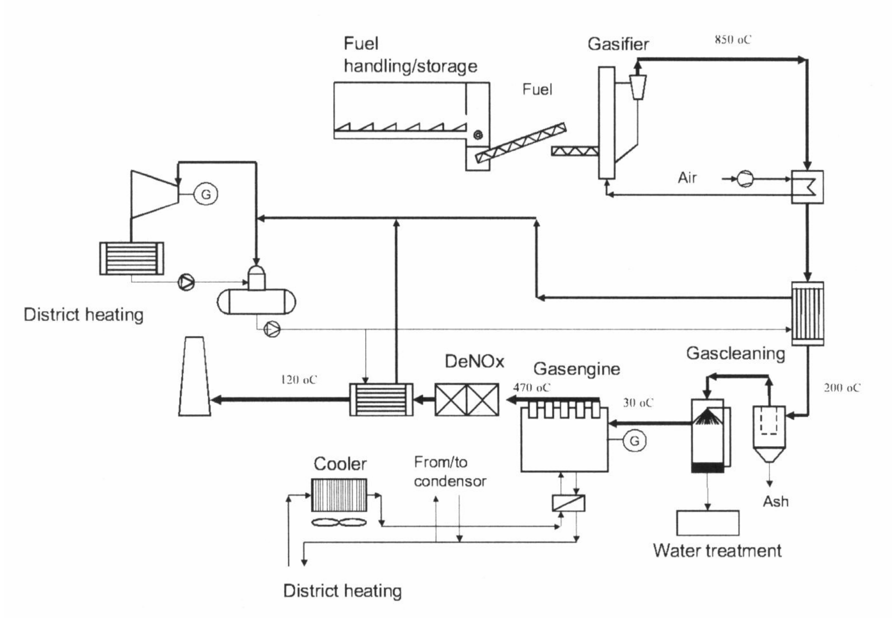

Figure 4. Flow sheet of the 14.7 MW_{th} BIVKIN-based power plant

The capital investment estimates for these scenarios are similar or better than other similarly sized gasification processes under development (as shown later in Table 4). The total efficiency of the plant is assumed to be 70% and 65% with and without the steam turbine, respectively. The efficiency drops to 66% and 61%, respectively, with the 40% moisture biomass. One of the conclusions that can be drawn is that the added steam turbine does not warrant the extra investment at these scales. The cost of the electricity ranges from 5-7¢/kWh when the fuel cost is $0-1.5/GJ ($0-1.58/Btu) and 8-11¢/kWh when the fuel cost is $2-4/GJ ($2.11-$4.22/Btu) (clean biomass).

1.1.1.3 Brightstar Synfuels Co./Brightstar Environmental

Brightstar Synfuels, Co., (BSC) developed a gasification concept in 1989 with tests in a 25-90 kg/h (55.1-198.4 lb/h) pilot plant. They subsequently scaled up to a commercial unit in 1994 at a particleboard plant. The plant had a capacity of 17,600 kg/h (38,801 lb/h) of sander dust. It was terminated in 1995 because of problems with the heat recovery equipment used in the gas cooling system. A free standing Commercial Demonstration Facility (CDF) was built near Baton Rouge, Louisiana, in 1996 with design throughput of 680 kg/h (1,499 lb/h). The facility was operated continuously to prove the concept and refine the process. This facility was considered a commercial scale facility because of the "tubular entrained flow" design. Multiple gasifiers would be used in larger capacities. Various feedstocks such as sawdust and sander dust, bark and wood chips, pulp and paper mill sludge, rice hulls, sugar cane bagasse, and sewage sludge were tested. Louisiana State University's Institute for Environmental Studies supported the demonstration plant in Louisiana. The syngas produced from the system had the following composition: 30-40% H_2, 20-30% CO, 10-15% CH_4, 15-20% CO_2, 1% C_2H_4, 6% water, and 1% N_2.

The major steps in the Brightstar process are:

1. Delivery of biomass to a metering bin from which it is conveyed with recycled syngas or steam without air or oxygen into the gasifier.
2. Reforming of material into hot syngas that contains the inorganic (ash) fraction of the biomass and a small amount of unreformed carbon.
3. Recovery of sensible heat in the hot syngas to produce heat for the reforming process.
4. Cleaning of the cool syngas through a filter and removal of the particulate in the syngas to produce a dry, innocuous waste. Clean syngas is then available for combustion in engines, turbines, or standard natural gas burners with minor modifications.

Brightstar entered a license agreement and strategic alliance with Energy Developments Limited (EDL) of Australia to commercialize the Brightstar process in Australia for municipal solid waste (MSW) feedstock. EDL became a major shareholder in Brightstar (Juniper Consultancy Services Ltd, 2000). BSC became a subsidiary for EDL as Brightstar Environmental.

The waste-to-energy concept that is being developed in Australia is called SWERF™ (Solid Waste Energy and Recycling Facility). A schematic diagram of the SWERF™ technology is shown in Figure 5 (www.brightstarenvironmental.com).

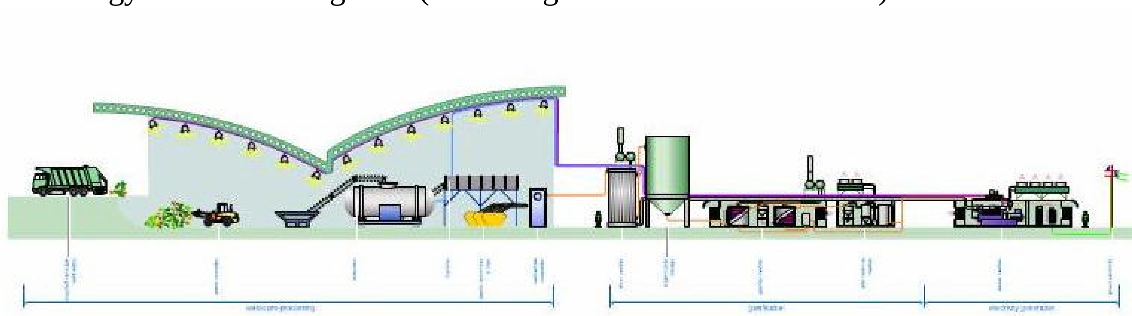

Figure 5. Schematic Diagram of the SWERF™ Technology

The facility initially converts green wood waste to electricity using the Brightstar gasification process. The first plant is built near Wollongong City Council's Whytes Gully landfill site in New South Wales, Australia (www.wollongong.nsw.gov.au). The site was commissioned on May 18, 2000. It was designed to process green organic materials such as urban tree toppings at 20,000 metric ton/a (22,046 ton/a). The syngas is burned with natural gas to produce electricity. The second phase will extend this to process 150,000 metric ton/a (165,345 ton/a) (of MSW to generate 120 GWh/a of electricity. The final design would consist of four gasifiers and eight generator modules. The plant was completed and opened in 2001. During the test period the plant was ramped up to a throughput level equating to about 60% of the nameplate capacity measured at the primary gasifier. One of the problems from the system was the carry over of fine char particles from the gasifier vessel with the gas stream. The other systems have performed to expectations. Modifications to the char gasifier are planned to prevent the aforementioned problem. Brightstar is planned to complete the nameplate capacity late this year before the start of the next SWERF™ projects (www.planktark.org/dailynewsstory.cfm/newsid/14214/story.htm). An aerial photo of the Whytes Gully facility in shown in Figure 6 (www.brightstarenvironmental.com/html/News/newstext.htm).

Figure 6. Aerial Photo of the Whytes Gully Facility in Wollongong

The key air emissions for the Whytes Gully site is summarized in Table 2 (http://www.brightstarenvironmental.com/html/env%20frame%20set/tables.htm)

Table 2. Summary of Emissions for Whytes Gully Site

Emissions	License Limit, mg/Nm^3	Engine, mg/Nm^3	Reformer, mg/Nm^3
Acid gases of chlorine (HCl)	41	0.02	0.01
Dioxins and furans (TEQ)	9.3	<0.03	<0.03
Oxides of Nitrogen (NO_x)	308	152-208	24-68
Sulphur Dioxide (SO_2)	86	20.5	<30
Particulate Matter (PM)	24	2.6	Not tested
Cadium and Tellurium (Cd and Ti)	0.02	0.005	0.0005
Mecury (Hg)	0.02	0.0056	0.0056
Lead (Pb)	0.20	<0.0009	<0.0009
Hydrogen Sulphide (H_2S)	No level assigned	0.001	0.001

Brightstar Environmental has signed a contract with Derby City Council in Britain to recycle and recover resources from the waste in and around Derby (www.brightstarenvironmental.com/derby/text.htm). This facility will process 50,000 metric ton/a (55,116 ton/a) of waste and generate around 5 MW of electricity. The SWERF™ facility will be build at Sinfin Lane, on a site formerly occupied by a tannery. The construction is expected to start in 2002 with plant opening in late 2002. Brightstar is also in the early stages of developing the SWERF™ facility in Kent in conjunction with Brett Waste Management in Britain.

1.1.1.4 Cratech Gasification System

Western Bioenergy funded Cratech in Tahoka, Texas, in 1998 to develop a gasification project for converting straw, grass, and shells (www.westbioenergy.com). A 1 MW unit was developed and tested. The Cratech gasifier is a pressurized, air-blown fluidized-bed reactor. Biomass is injected with a biomass pressurization and metering unit. The product gas is passed through a hot-gas cleanup system followed by injection into a turbine combustor. The system uses the higher practical thermodynamic efficiency of the Brayton cycle over the Rankin cycle. A flow diagram of the Cratech process is shown in Figure 7 (Purvis and Craig, 1998).

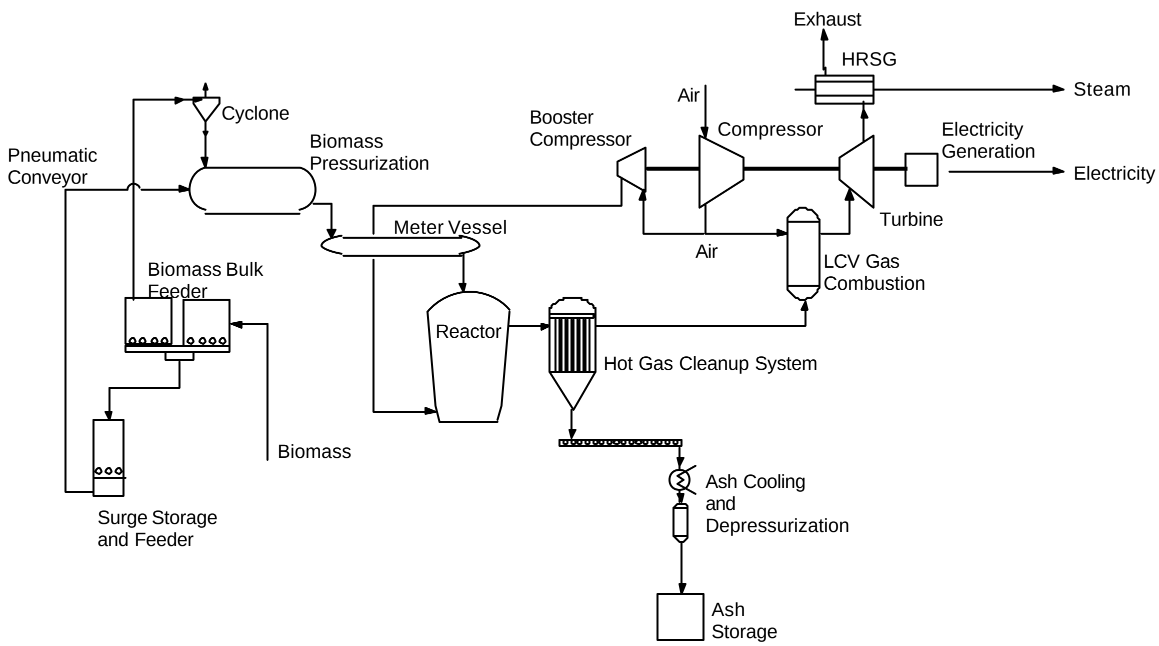

Figure 7. Cratech Gasification System (Purvis and Craig, 1998)

The maximum design pressure of the Cratech system is 1,353 kPa (202.8 psi) at a feed rate of 1,996 kg/h (2.2 ton/h) of wood at temperatures below 730 °C. The syngas is cleaned by a hot-gas filter and is directed to the combustion chamber of a gas turbine engine. Wet scrubbers are not used. Catalysts and higher temperatures are not needed for tar destruction before combustion. The composition of the syngas is 10.4% H_2, 3% CH_4, 17% CO, 15.3% CO_2, 41% N_2, 12% H_2O, 1 % C_2H_4, and 0.3% C_2H_6. The lower heating value of the syngas is 5.18 MJ/scm (139 Btu/scf). The Cratech system can fuel a turbine of 1.5 MW_e with a maximum pressure ratio of about 11.0. The initial gas turbine combustion test was performed with a Solar Spartan turbine rated at 225 kW_e with a pressure ratio of 4.0. An EGT Typhoon gas turbine was designed to operate on the low heating value syngas.

1.1.1.5 Energy Products of Idaho

Energy Products of Idaho (EPI) of Coeur d'Alene, Idaho, claimed to design and build the first fluidized bed combustor for firing wood which also operates on 100% paper sludge

(Inland Empire Paper Company, Spokane, WA) (www.energyproducts.com). EPI has designed and supplied more than 79 gasification plants worldwide since 1973. Their expertise is in atmospheric fluidized-bed (AFB) gasifiers. The bed material can be either sand or char or a combination of both. The fluidizing medium is usually air. Their AFB can process fuel with moisture contents up to 55% and high ash contents over 25%. Temperature is maintained below the fusion temperature between the ash and the slag which increases the utilization of the slagging fuels. The product gas is cleaned by cyclones. The heating content of the gas is about 7.4 MJ/scm (200 Btu/scf). The EPI website listed a total of 63 operating units in the world. These facilities process a wide variety of biofuels such as wood waste, bark and wood chips, RDF, hogged fuel, agricultural waste, urban wood waste, coal, polyethylene terephthalate, and polyvinylbutyryl. Most of these plants produce heat and steam. Several plants produce electricity in the range of 25 to 50 MW_e. One plant was scheduled for start up October 2001 in Verzuolo, Italy, for heat and steam production using paper sludge and wood waste feedstocks. Another system is scheduled for start up in the fall of 2002 at Trus Joist Weyerhaeuser in Northwest Ontario, Canada, for heat and steam generation.

1.1.1.6 Enerkem–Biosyn Gasification

The Enerkem-Biosyn gasification process has a long history of development in Canada. Many transformations have occurred over the past decades (http://solstice.crest.org/renewables/bioenergy-list-archive/9612/msg00266.html). Canadian Industries Limited (CIL) was formed in the early 1970s as a wholly owned Canadian subsidiary of Imperial Chemical Industries (ICI). CIL initiated the OMNIFUEL program to develop a versatile fluidized-bed technology to convert its industrial wastes into useful syngas for either energy or chemical synthesis. A pilot plant was constructed in Kingston, Ontario. This was discontinued after CIL restructured. BBC Engineering was formed and installed a 10 metric ton/h demonstration gasifier coupled to a boiler at the Levesque sawmill in Hearst, Ontario. The economics did not favor the commercialization of the process despite its technical success.

Canertech was created in the late 1970s by the Canadian government to promote alternate energy sources. Nouveler, a subsidiary of HydroQuebec, formed a joint venture, Biosyn Inc., with Canertech to demonstrate the gasification of biomass and the conversion of the syngas to methanol. A 10 metric ton/h (11.0 ton/h) gasification plant was designed and erected by SNC, a Montreal-based engineering firm, and BBC Engineering at St. Juste de la Bretenniere, Quebec. The gasifier was a pressurized reactor with maximum pressure of 1,600 kPa (232 psi). The demonstration proceeded from 1984 to 1986. Over 1,600 hours were operated in the gasification mode and over 600 hours were operated with coupling to a 750 kVA Alstrom generator. Canertech was dissolved in 1984, and Nouveler became the sole owner of Biosyn, Inc. Biodev, Inc., was a joint venture between Nouveler and SNC to commercialize the Biosyn technology. A demonstration project was secured in Guyane, France, to produce 7.5 MW of electricity. The plant was constructed and briefly operated. It was abandoned in the late 1980s, and Biodev was dismantled. Biothermica Ltd., was formed as an independent company to continue to pursue the commercialization of the licensed Biosyn technology. The gasification plant and the sawmill at St. Juste were sold to a sawmill company, BECESCO, in 1989. The gasification plant remained at the sawmill.

The intellectual property generated by Biosyn was transferred to Centre Quebecois de Valorisation de la Biomasse (CQVB) in 1989. CQVB, a provincial corporation, launched a program to use the gasification technology to process forest waste, agricultural waste, MSW and RDF, and industrial wastes. A research program was started in 1990 at Université de Sherbrooke. Research was carried out using a 50 kg/h (110 lb/h) gasifier that was built by IREQ. It was then transferred to Sherbrooke, and a PDU facility was built around the gasifier. A flow diagram of the PDU is shown in Figure 8.

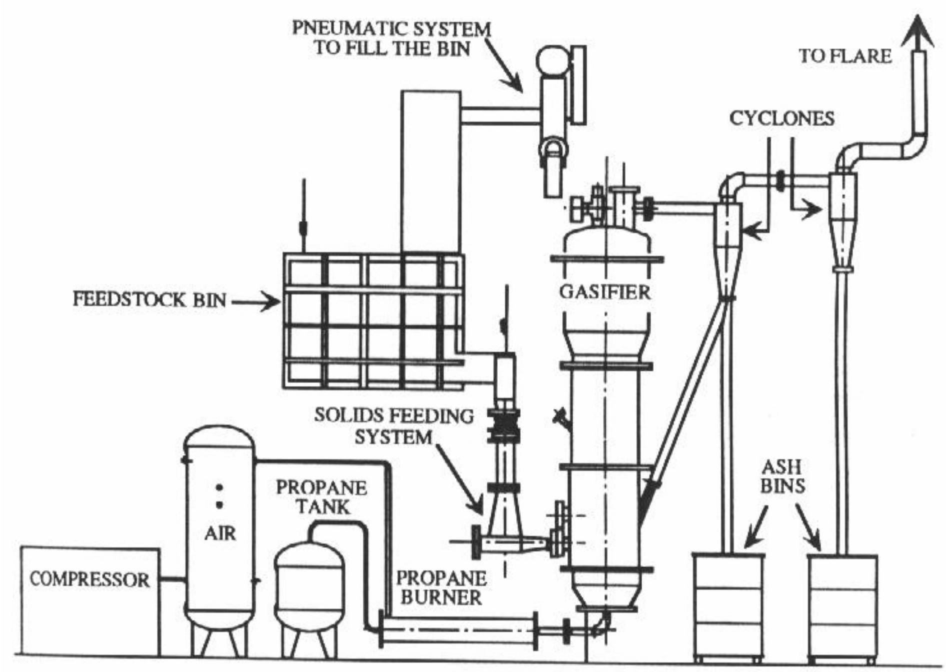

Figure 1. Process flow diagram of the gasifier installation having a nominal capacity of 500 kg/h of biomass.

Figure 8. Biosyn PDU at Université de Sherbrooke (Czernik, 1993)

A partnership between Université de Sherbrooke and National Research Council of Canada led to the creation of the Groupe de Recherche sur les Technologies et Procédés de Conversion (GRTPC) for fundamental and applied research in biomass conversion. Kemestrie, Inc., was formed in 1993 as a spin-off company from Sherbrooke to advance the commercialization efforts. A 100-kg/h (220 lb/h) unit was installed at a metallurgical plant in Quebec to recycle aluminum from post-consumer packaging. The environmental division of Kemestrie, Inc, Enerkem Technologies Inc., was established in 1998 to commercialize the environmental energy and coproducts technologies. Biothermica continues to focus on the larger capacity energy conversion markets. A demonstration unit is also located at Alcan in Arvida, Quebec, in addition to the PDU at Sherbrooke.

The Biosyn technology is a bubbling fluidized-bed gasifier with cold or hot syngas purification system. The biofuel is limited to a maximum of 5 cm (1.96 inch) with a maximum moisture content of 20-25%. Gasification occurs at temperatures between 700 and 900 °C (1,292 and 1,652 °F). Average high heating content of the syngas is 6 MJ/Nm^3, and a higher heating content of 12 MJ/Nm^3 can be obtained with oxygen injection. The syngas is cleaned by a cyclone system to remove 90-95% of the solid particles. Both the washing and filtration system can be used to purify the gas further. The typical composition of the syngas by volume is 16% CO_2, 12-30% CO, 2-10% H_2, and 55% N_2. The syngas also contains small percentages of light hydrocarbons, oxygen, solid particles, tar, and other elements. The estimated cost of the system when coupled to energy production varies from $1,500 to $2,000/kW (www.enerkem.com).

1.1.1.7 PRM Energy Systems, Inc.

PRM Energy systems, Inc., founded in 1973, has many years of experience in biomass gasification for electricity and heat generation. Their website contains information on their various commercial and demonstration projects around the globe. The gasification technology was developed at Producers Rice Mill, Inc. (PRM). The first two gasifiers were installed in 1982 to gasify rice husks to produce process heat and steam for a large rice parboiling facility. Many biomass feedstocks were tested between 1984 and 1988 in a full-scale PRM gasifier. These include rice hulls, rice straw, chicken litter, green bark, sawdust and chips, peat, wheat straw, corn cobs and stubble, peanut hulls, RDF (fluff, flake, and pellet), petroleum coke, cotton-gin waste, cotton-seed hulls, and low-grade coal. The rice residue gasification has been in operation since 1982 in U.S., 1985 in Australia, 1987 in Malaysia, and 1995 in Costa Rica.

The PRM gasifier is a vertical cylindrical steel shell with reduced diameter in the upper section. The inside is lined with refractory material that can withstand temperatures as high as 1,560 °C (2,840 °F). The feed rate of the fuel and the out feed conveyor for ash are controlled by the preset temperature of the gasifier. Gasification is carried out with the addition of 10-12% of the stoichiometric air requirement. Partial combustion of the fixed carbon occurs in the gasification zone. Gases are burned in the combustion tube and chamber which also promotes thermal cracking of tars and hydrocarbons. The clean, low BTU content gas can be used for drying applications or in the radiant section of the boiler.

A gasification plant was installed in Greenville, Mississippi, in 1995 with a thermal and net electric output of 17.5 MW_{th} and 6.5 MW_e, respectively, using rice husk feedstock. Another system was installed in 1996 in Stuttgart, Arkansas with 63 MW_{th} and 12 MW_e output also with rice husk feedstock (Biomass Technology Group: www.btgworld.com).

A gasification plant which includes a cleanup system and IC engine/generation was scheduled for completion in 2001 for Rossano Energia, SpA in the south of Italy for processing olive residue (sansa). It is expected to generate approximately 4.05 MW_{th} (gross) of electricity from 4,500 kg/h (9,920 lb/h) of sansa (www.prmenergy.com).

The PRM process is marketed by PRM Energy Systems itself as well as through Primenergy, Inc., for the U.S. and the Philippines. Grupo Guascor of Spain covers France, Italy, Spain, and Portugal (Juniper Consultancy Services Ltd, 2000). The PRM process is fully proven and has operated continuously at various scales.

1.1.1.8 Thermogenics

The Thermogenics gasifier is a directly heated, air-blown, continuous bottom fed, stratified updraft gasifier (Juniper Consultancy Services Ltd, 2000). It was designed specifically for processing MSW with a capacity of 0.5-3 metric ton/h (0.55-3.3 ton/h). The MSW is shredded and dried to a moisture content of 30% or less. It is introduced into the gasifier through the bottom. An external fuel source is used to heat the MSW to auto-thermal temperature. Gasification occurs around 980 °C (1,796 °F) at the bottom of the bed and 370 °C (698 °F) at the top. Char and particulates from the syngas are removed by a dust removal device and recycled to the gasifier. The syngas is cooled to condense the aerosols and passed through an electrostatic precipitator. The syngas can be used for power generation via gas engines or conventional boilers. The Thermogenics system has been reviewed favorably by NREL for MSW processing (Camp Dresser and McKee, 1996).

Thermogenics is cooperating with Power Energy Fuels, Inc., (PEFI) based in Lakewood, Colorado, to produce Ecalene™ as oxygenate for transportation. Ecalene™ is a mixture of ethanol and higher alcohols with a composition as shown in Table 3.

Table 3. Composition of Ecalene™ (Power Energy Fuels)

Component	Percent (by wt)
Methanol	0
Ethanol	75
Propanol	9
Butanol	7
Pentanol	5
Hexanol and Higher Alcohols	4

The Ecalene™ is produced by passing the syngas through a proprietary molybdenum sulfide catalyst. The molybdenum sulfide catalyst is developed at PowerEnerCat, Inc. Both of these companies shared the same C.E.O., G.R. Jackson. Furthermore, development of the catalytic conversion of syngas to Ecalene™ is currently underway at Western Research Institute (WRI) located in Laramie, Wyoming. WRI is testing the catalyst for natural gas and landfill gas using a 1.89 m^3/day (500 gal/day) pilot (Lucero, 2001). This catalyst was first studied at Dow and Union Carbide for alcohol production. A schematic diagram showing the bench-scale facility at WRI is shown in Figure 9.

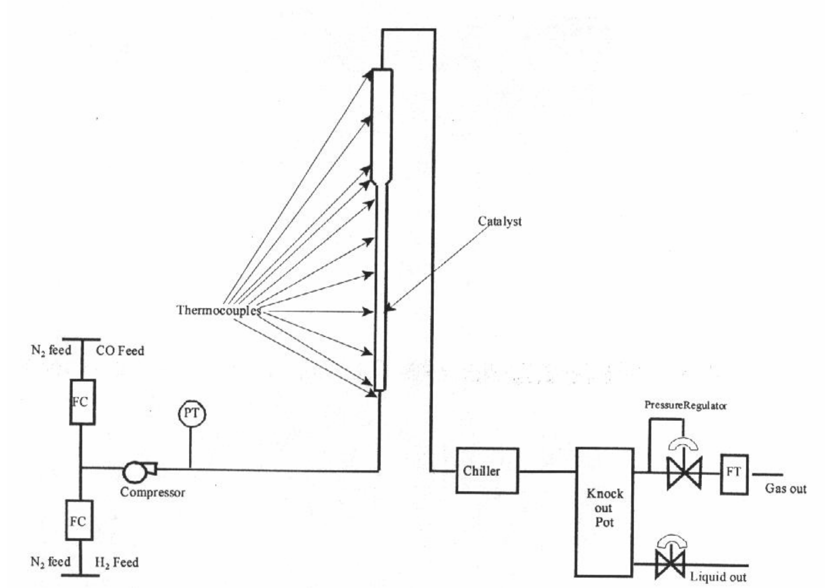

Figure 9. Flow Diagram of the 500-gpd Facility at WRI (Lucero, 2001)

It is not clear at this time whether Thermogenics is still working with PEFI to use the Thermogenics gasifier for the production of syngas for Ecalene™ production. PEFI is currently developing their own syngas from natural gas to produce the Ecalene™. A commercial demonstration facility is under development for this effort and is being fabricated by FabPro, LLC, in Denver, Colorado, for siting at WRI.

1.1.1.9 Thermoselect, S.A.

The development of the Thermoselect HTR (High Temperature Recycling) process began in 1989. A demonstration plant was built at Fondotoce in Italy and was operated for semi-commercial scale from 1994 to 1999. The process combines slow pyrolysis with fixed-bed oxygen-blown gasification and residue melting (Juniper Consultancy Services Ltd, 2000). The first stage of the process uses a high-pressure press to compact the feedstock to increase its bulk density, squeeze out entrained air, and homogenize the material by dispersal of liquids. The second stage involves the pyrolysis of the compacted material by indirect heating while it flows down the pyrolysis channel. The temperature varies from 100-200 °C (221-392 °F) at the entrance to over 800 °C (1,472 °F) at the transition point from the pyrolysis channel to the gasification reactor. A residence time of 1-2 hours is needed to convert the material to syngas and char.

Further reaction takes place in the gasification reactor with a residence time of 2-4 seconds and a syngas discharge temperature of 1,200 °C (2,192 °F). Oxygen is fed to the gasification reactor at a pressure of 100 kPa (14.5 psi). All the carbon char is converted to syngas comprising mostly H_2 and CO. The inorganic components such as metals and mineral materials are maintained in a molten stage between 1600-2000 °C (2912-3632 °F) with additional fuel gas. Slag in molten state is water quenched to form mineral chip and iron rich metal pellets for recycling.

The syngas from the gasification reactor is water quenched to below 70 °C (158 °F). Acid gases such as HCl and HF are removed by conventional scrubbing while H_2S is converted catalytically to elemental sulfur. The syngas is further processed to remove water vapor and passed through an activated carbon filter to comply with regulatory limits. The syngas can be used as a fuel source for power generation. A schematic diagram of the Thermoselect HTR process is shown in Figure 10.

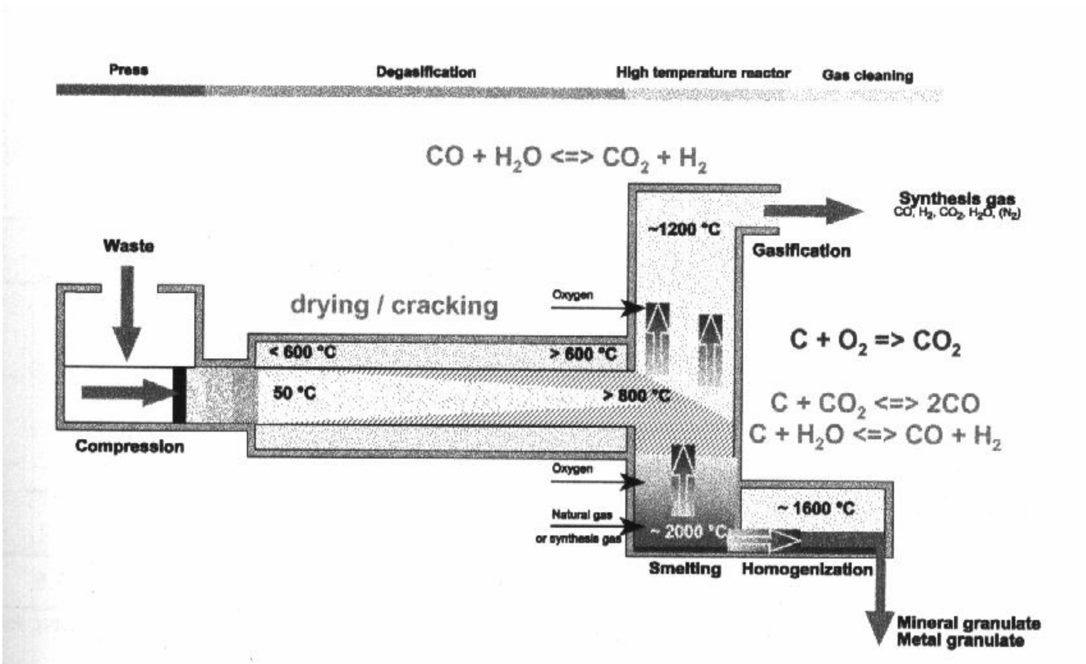

Figure 10. Thermoselect HTR Gasifier (Juniper Consultancy Services Ltd, 2000)

Many improvements have been made to the Thermoselect gasifier including increased throughput from 9.1 metric ton/h (10 ton/h) to 1.4 metric ton/h (12.5 ton/h), improved efficiency from the Jenbacher gas engines to 38.5%, preheating of the pyrolysis channel with waste heat, and increased energy efficiency of 41% when coupled to a combined heat cycle element employing an Organic Rankine Cycle (Juniper Consultancy Services Ltd, 2000).

The Thermoselect process is designed for specific needs at different locations. The plant at Karlsruhe, Germany (1999) uses three trains of the Thermoselect system to process 204,119 metric ton/a (225,000 ton/a) of MSW and produce 50 MW_{th} of heat for the district heating network. The plant at Ansbach, Germany (2000), has one train to process 75,000 ton/a of MSW, and a second train is scheduled to be added later. The thermal-to-electrical conversion efficiency is claimed to be 38.5%. The Thermoselect plant at Hanau, Germany, uses two trains to process 91,647 metric ton/a (90,000 ton/a) of MSW. The syngas is used for offsite power generation of 10.3 MW_e. A facility was built in Chiba, Japan, in 1999 with two trains to process 136.1 metric ton/day (150 ton/day) of MSW.

Interstate Waste Technologies, Inc. (IWT), has agreed to represent Thermoselect in the Western Hemisphere (PRNewswire, July 21, 2000). Some other developments can be found at IWT's website at www.interstatewastetechnologies.com. Thermoselect is the current leader in MSW processing in Europe. A detail report is provided by the publication by Juniper Consultancy Services Ltd (Juniper Consultancy Services Ltd, 2000). Camp Dresser and McKee has compared the Thermoselect process with six other MSW processing technologies for NREL under a DOE contract (Camp Dresser Report, 1996). They found that the Thermoselect facility is the most capital intensive at about \$237 million for a 1,440 Mg/day (1,587 ton/day) plant and also has the highest operating cost at \$94.92/Mg (\$86.11/ton). On the other hand, it has the highest net heat rate at 13.55 MJ/kWh (12,843 Btu/kWh).

1.1.1.10 TPS Termiska Processer AB

In the 1970s, Studsvik of Sweden diversified into other areas of energy development aside from nuclear. The Thermal Engineering Laboratory assumed the responsibility of the circulating fluidized-bed gasification technology called the MINO process (Juniper Consultancy Services Ltd, 2000). Studsvik operated the MINO 2.5-MW pilot plant at up to 2,027 kPa (294 psi) from 1979-1986 (Blackadder, 1993). Figure 11 shows the MINO process with a high-temperature filter. The integrated gasification combined cycle (IGCC) concept failed because of the lack of interest from the Swedish government.

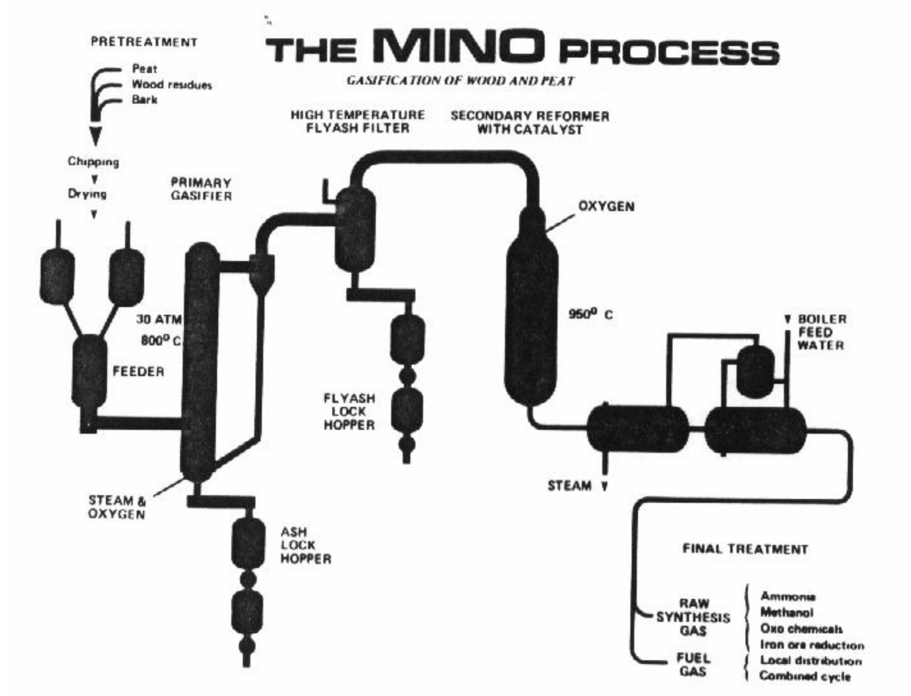

Figure 11. The MINO Gasification Process

TPS Termiska Processer AB was established as a private company in 1992 to pursue the CFB for small- to medium-scale electricity production using biomass and RDF as feedstocks. TPS began work on the development of atmospheric pressure gasification for converting wood, peat, RDF, and other reactive solid fuels to energy in 1984. The gasification technology involves an air-blown circulating fluidized-bed (CFB) gasifier. It operates at 850-900 °C. The tarry product gas has a tar content of 0.5-2% of dry gas with a heating value of 4-7 MJ/Nm^3 (107.4-187.9 Btu/scf). The system is favorable for fuel capacities greater than 10 MW_{th}. The characteristics of the TPS system are good fuel flexibility, compactness and cost-effective large-scale construction, good controllability and low-load operation characteristics, uniform process temperature due to highly turbulent movement of solids, optimum gas quality (high carbon conversion), no extensive fuel treatment required, and fines recycling from a secondary solids separator (Rensfelt, 1997).

The 2 MW_{th} CFB pilot plant at TPS was erected in 1986. A schematic diagram of the CFB gasifier is shown in Figure 12.

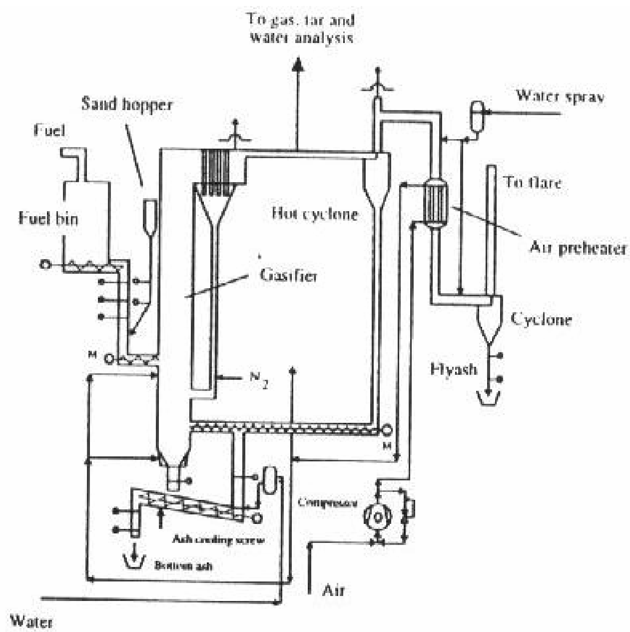

Figure 12. TPS ACFB Gasifier

Feedstocks such as bark, wood/PVC mixture, and RDF were tested in late 1986 and 1987. A variety of other feedstocks were also tested in subsequent years of development. In 1987, a dolomite-containing CFB tar cracker, a cold-gas filter, a wet scrubber, and a modified 500-kW shaft-powered, turbo-charged, eight-cylinder, dual-fuel, diesel engine were installed at the pilot plant. Extensive research has been done using a second reactor as a tar cracker. Figure 13 shows the flow diagram of the process at the pilot scale. The tars in the syngas are cracked catalytically by dolomite in a separate vessel at about 900 °C (1,652 °F) immediately downstream of the gasifier.

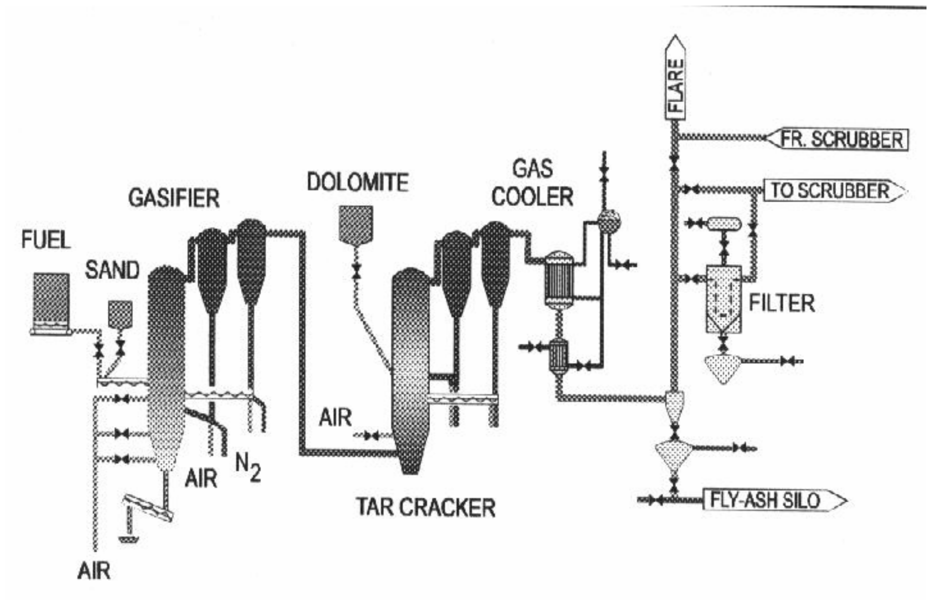

Figure 13. TPS Pilot Plant with Tar Cracker

The CFB license was sold to Ansaldo Aerimpianti SpA for the construction of a waste-fueled gasification plant in Grève-in-Chianti, Italy (Rensfelt, 1997). The plant was commissioned in 1992 and has a total capacity of 200 metric tons (220.5 tons) of RDF per day using two 15-MW_{th} CFB gasifiers. The gasifiers operate at close to atmospheric pressure at about 850 °C (1,562 °F) using air as the gasification/fluidizing agent. A process flow sheet is shown in Figure 14.

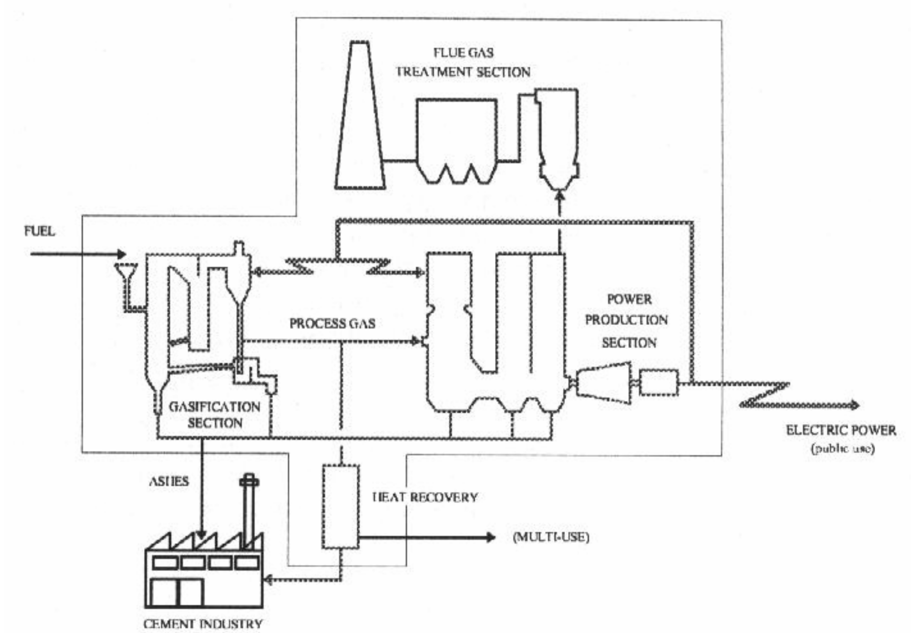

Figure 14. Flow Diagram of the TPS Gasification System for RDF in Grève-in-Chianti, Italy

The raw syngas passes through two stages of solids separation before being fed to a furnace/boiler. The flue gas is cleaned in a three-stage dry scrubber system before being exhausted through the stack. The steam produced in the boiler is used to drive a 6.7 MW_e steam condensing turbine. The tar cracker was not installed at the Grève-in-Chianti plant, and an additional line was planned which will incorporate a CFB tar cracker (Juniper Consultancy Services Ltd, 2000).

TPS started to promote the use of the ACFB system for biomass integrated gasification combined cycle (BIGCC) application in 1990 after extensive evaluation of the technology. TPS was chosen to supply the gasifiers for the BIG-GT project in Brazil and the ARBRE Energy project in the UK. The ARBRE project was scheduled for operation in 2001 (Biomass Technology Group) using hot-gas clean up technology developed at TPS (Morris, 2000). The major activities of the $100 million BIG-GT project in Brazil were started in 2000 (TPS Newsletter, May 2000). The BIGCC concept that is offered by TPS is shown schematically in Figure 15.

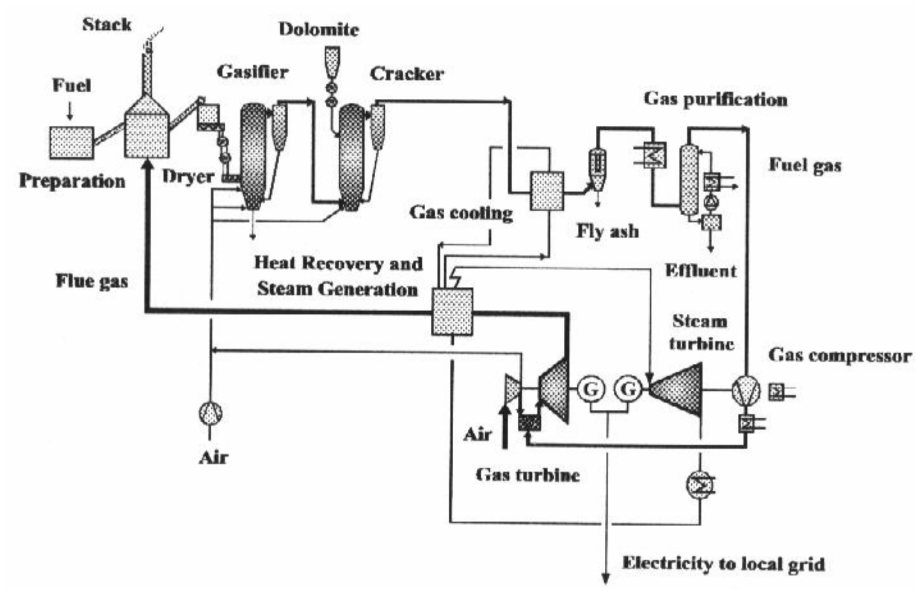

Figure 15. TPS BIGCC Concept (Morris, 2000)

The system generates low heating value fuel gas at about 6-7 MJ/Nm^3 (161-187.9 Btu/scf). The tars are cracked in a tar cracker with dolomite at 900 °C (1,652 °F). The fuel gas is cleaned by a filter and wet scrubbing. In addition, the ammonia is dissolved in water to reduce NO_x formation from fuel nitrogen. According to TPS, the advantages of the atmospheric pressure BIGCC technology over pressurized technology are:

1. less required development and reliable operation,
2. simpler fuel and ash handling systems,
3. more reliable gas purification – use of gas scrubber ensures that the product gas is of sufficient quality for gas turbine operation,
4. higher heating value of the product gas,
5. supplementary firing of the heat recovery steam generator allows plant output to be boosted,

6. weak process coupling between gasifier and gas turbine, and
7. greater possibilities to use difficult feedstocks (eg. waste).

1.1.1.11 Thermal Technologies, Inc.

A project at Camp Lejeune, North Carolina, was sponsored by the U.S. EPA and U.S. DOD Strategic Environmental Research and Development Program (Cleland, 1997). The Research Triangle Institute (RTI) is working under a Cooperative Agreement with EPA to complete the testing and demonstration. Other participants are the Marine Corps, North Carolina Department of Commerce, and Thermal Technologies, Inc. (TTI). The gasification technology used is the downdraft moving-bed gasifier from TTI, and the process flow sheet is shown in Figure 16.

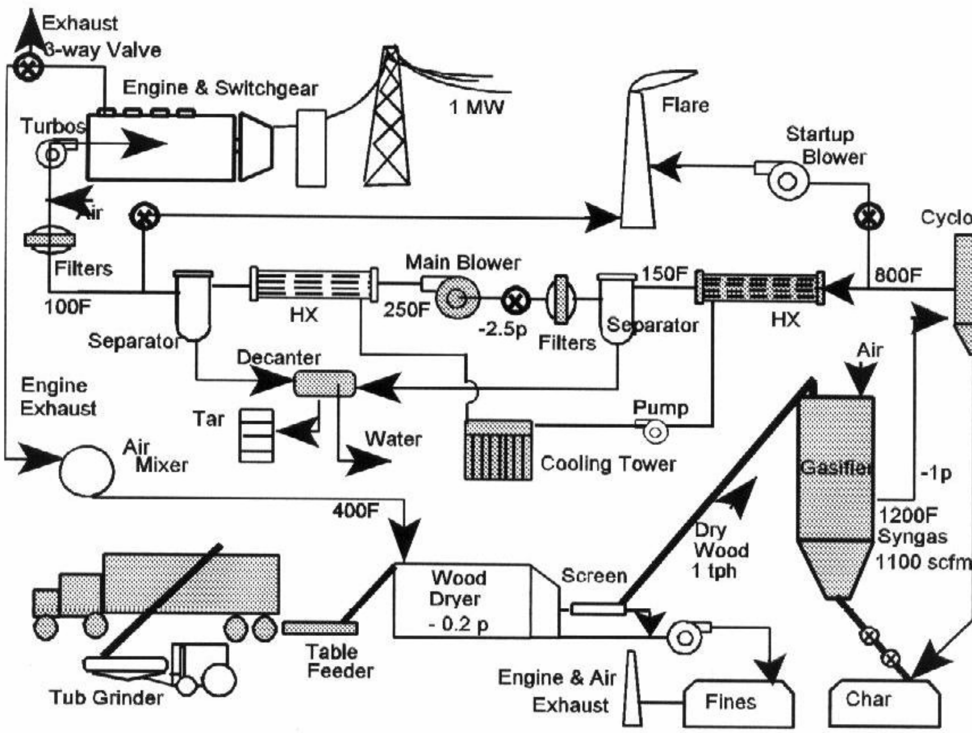

Figure 16. Camp Lejeune Energy from Wood (CLEW) Project

The gasifier has a dimension of 2.1 m (7 ft) in diameter, 2.4 m (8 ft) deep char bed, and a 0.305 m (1 ft) deep pyrolysis zone. The wood gas is about 2.83 m^3 (100 scf) with a higher heating value of 6.33 m^3 (170 Btu/scf) and a maximum gasifier temperature of 816 °C (1,500 °F). This project uses gasification to supply the wood gas for an IC, spark-ignited, reciprocating engine for electricity generation. The Waukesha L7042 GSI turbo-charged engine and generator is used which is rated at 1 MW electricity on natural gas and 700 kW on syngas from wood. The output from the engine is below 500 kW during operation. The syngas is cleaned by a cyclone, cooled by a tube-in-shell heat exchanger, and tar and water removed by a coalescing liquid separator. There is no hot-gas filtration employed in the system. The syngas has a composition of 18% CO, 19% H_2, 14% CO_2, 5% CH_4, and 44% N_2. Wood residues within short distance are used as feedstock. Large wood particles for this system reduce fuel requirements for the drying. The system requires simple controls and minimum labor. The installed cost for this system is estimated to be $760/kW because of the reduced equipment investment.

1.1.1.12 Etho Power Corporation

Etho Power Corporation is a privately owned company located in Kelowna, British Columbia, Canada. Etho Power developed a proprietary biomass electricity generating system that utilizes gasifiers, heat exchangers, and air turbines. It is claimed that the Etho system is more efficient, produces less emissions, and is less expensive than traditional biomass gasification systems. A demonstration system is located in Kelowna, British Columbia. The project is funded by the British Columbia provincial government, BC Hydro & Power Authority, and the National Research Council of Canada. Little information could be found on the gasification technology.

Maxim Power Corporation announced on January 18, 2001, that it has entered an agreement with Etho Power. Under the agreement, Maxim will have an exclusive license for the utilization of the biomass-to-electricity and/or thermal recovery technology in Mexico, the Caribbean, and Central and South America. Maxim will also co-market with Etho Power globally as a provider of "Build, Own Operate" services for purchasers of the Etho Power Systems (Maxim Power Corp., News Release 1/18/01).

Etho has completed commissioning of its first commercial gasification system at Princeton Wood Preservers, Ltd. (British Columbia). Waste wood is gasified to produce thermal energy to substitute for natural gas at the plant. A second commercial gasification system was delivered to Visy Paper Pty. in Australia in 2001. Waste paper and plastics are scheduled to be gasified at this plant to produce thermal energy to offset natural gas consumption. The gasification system costs about $1,800,000. Etho and Visy have entered a four-year agreement worth an estimated $25 million dollars to supply six gasifiers or gasification-to-electricity power plants in Australia and United States. A demonstration plant funded by the Illinois-based Coaltec Energy will be used to demonstrate the gasification of waste coal tailings. Coaltec has secured $2,000,000 from the Illinois Clean Coal Review Board to support the project. Approximately $540,000 will be spent on building and operating the gasifier. The remaining monies will be used to fund a portion of the capital cost for the first commercial gasification-to-electricity installation (Maxim Power Corp., News Release 10/9/01).

1.1.1.13 Emery Gasification

Emery Gasification is based in Salt Lake City, Utah. It has developed a proprietary gasification technology for power production, chemical synthesis and industrial gases. It started the development in 1993. A 22.7-metric ton/day (25 ton/day) fixed-bed, air-blown gasifier was designed and built. It has been operated for over 2,100 hours during a 20-month test period from late 1996 to the fall of 1998 with scrap tires as the principle feedstock. Biomass and MSW were also tested. A picture of the gasifier is shown in Figure 17.

Figure 17. Emery's 25 ton/day Gasifier.

Emery Gasification technologies are covered by patents 5,573,559 and 5,787,822. Emery is also developing a novel multi-pollutant control process that removes the pollutants from the flue gas stream of coal-fired power plants at high efficiencies (www.emerygas.com).

In 2001, Emery formed a relationship with Idaho National Energy and Environmental Laboratory (INEEL) and successfully obtained a grant from the Department of Energy in to develop an advanced biomass gasification/power system. Additional partners are Combustion Resources, LLC, Biomass Energy Foundation, and the Southeastern Public Service Authority (SPSA). Emery is actively pursuing other funding opportunities to further develop their biomass- and coal-based gasification systems.

1.1.1.14 Other Biomass Gasification Developments

Several other developments in biomass gasification for heat and power are summarized in Table 4. These are found at the website of Biomass Technology Group.

Table 4. Current Developments on Biomass Gasification for Heat and/or Power Generation (BTG)

Location	Year Installed	Plant Owner	Manufacturer	Gasification Technology	Electric Output, MW_e		Thermal Output, MW_{th}	Feedstock	Gas Treat-ment	Capital Cost
					(Gross)	(Net)				
Harbo¢re, Denmark	1994	Ansaldo Vølund	Babcock Wilcox Vølund	Vølund R&D Centre, updraft counter-current fixed bed gasifier	1.5	1.0	3.2	Wood chips, 1-8 cm (0.39-3.15 in), 30-55% water	cooler, cyclone, wet electro-statical precipit-ator, wet scrubber	$5.5 million
Elsterwerda, Germany	2000/ 2001	Elbe-Elster Holzkraft AG	PPS Pipeline Systems GmbH	PPS Pipeline Systems, downdraft co-current fixed bed gasifier	4.5	3.9	7.5	Clean wood, demolition wood, waste wood, and wood chips, 2-20 cm (0.79-7.9 in), <35% water	cooler, cyclone	$15 million
Siebenlehn, Germany	1999	Sachsenhol z, AG	PPS Pipeline Systems GmbH	PPS Pipeline Systems GmbH	2.3-2.4	1.8-2.0	4.5	Clean wood, demolition wood, waste wood, and wood chips, 2-20 cm (0.79-7.9 in), <35% water	cooler, cyclone	$10 million
Eye, Suffolk, UK	2001, under construction	unknown	unknown	unknown		5.228	na	Short rotation coppice, wood chips	unknown	
Cricklade North Wiltshire, UK	2001, under construct-ion	unknown	unknown	unknown		5.528	na	Short rotation coppice, wood chips	unknown	

1.1.2 Advanced Biomass Gasification Systems

Advanced gasification systems generally involve integration with higher efficiencies and produce heat or combined heat/power generation. These systems are necessary for the Western countries for controlling of greenhouse gas emissions. Seven companies that have advanced gasification systems are reviewed.

1.1.2.1 Foster Wheeler Gasification Technologies

Foster Wheeler owns several gasification patents and gasification technologies. Some of these were developed by Ahlstrom Pyropower (API). Foster Wheeler acquired API and has likewise acquired these gasification technologies. The different gasifiers are the atmospheric updraft gasifiers (Bioneer), atmospheric circulating fluidized-bed gasifiers (Pyroflow), and the pressurized circulating fluidized-bed gasifiers (Bioflow). These are described below.

1.1.2.1.1 Bioneer Atmospheric Updraft Gasifiers

Foster Wheeler developed the atmospheric updraft gasification technology for converting biomass to heat for small districts. These are known as the BIONEER gasifiers. A total of ten BIONEER gasifiers have been installed. The maximum plant size is 10 MW_{th} fuel input with most of the plants in the range of 3-8 MW_{th} input. The can not be operated with sawdust or other smaller components because the feedstock is too fine to be effective in the process. These gasifiers are simple to operate, and the technology is well proven.

1.1.2.1.2 Pyroflow Atmospheric Circulating Fluidized-Bed Gasifiers

The next generation of gasifiers from Foster Wheeler is known as the Pyroflow gasifiers. They are atmospheric circulating fluidized-bed gasifiers (ACFB) developed in the 1980s by API as shown in Figure 18.

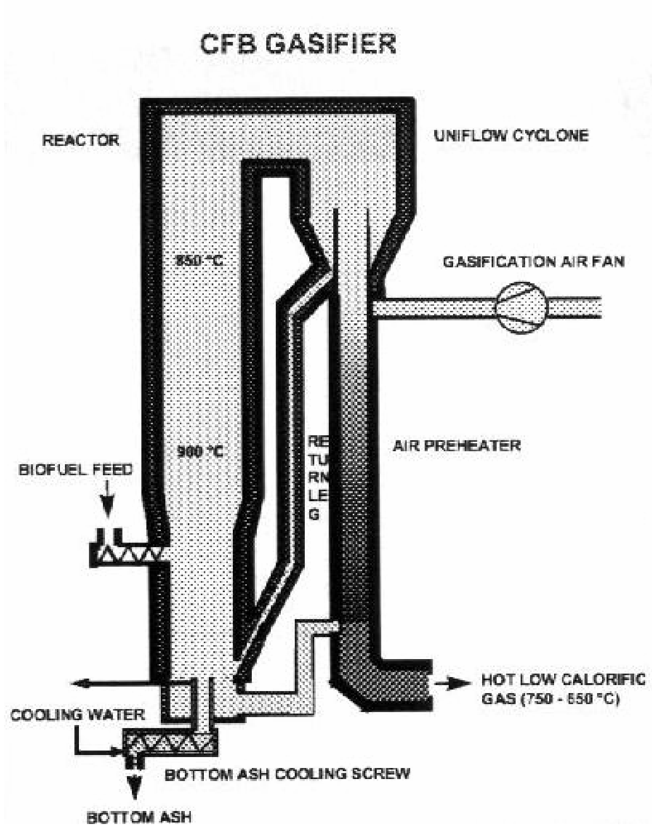

Figure 18. Foster Wheeler's Pyroflow ACFB Gasifier

The first commercial installation by Foster Wheeler Energia Oy in 1983 was to Wisaforest Oy pulp and paper plant in Pietarsaari, Finland, with a 35 MW capacity (Engström, 1999). Two more units were installed in two pulp mills in Sweden (Norrsundet Bruk Ab, Norrsundet, Sweden and ASSI, Karlsborgs Burk, Sweden) in 1985 and 1986, both 27 MW. Another 17 MW unit was installed at Portucell pulp mill in Rodao Mill, Portugal, in 1986. A fifth installation in 1998 was at Kymijärvi Power Station in the city of Lahti in southern Finland. This plant is operated by Lahden Lämpövoima Oy. A flow diagram of the gasification process for heat and power at Lahti is shown in Figure 19. A picture showing the site of the gasification plant is shown in Figure 20.

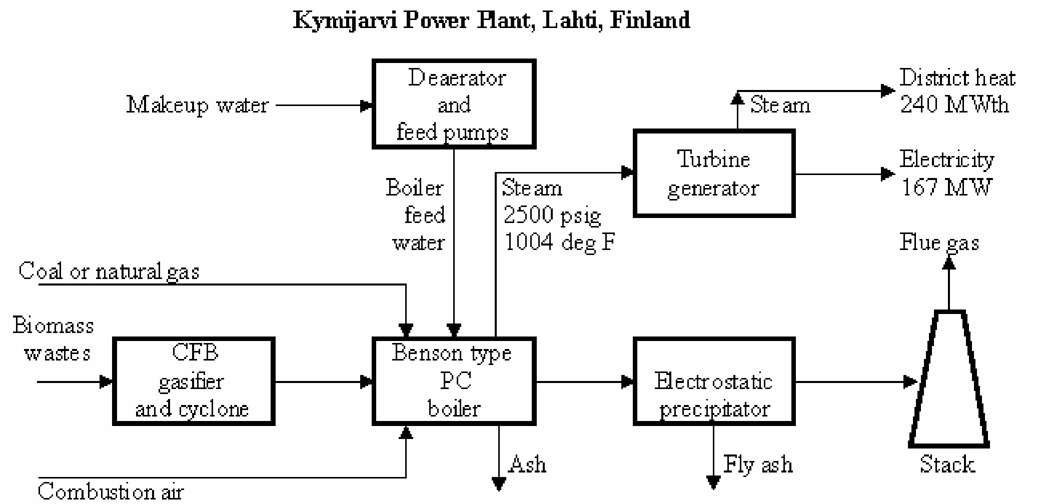

Figure 19. Flow Diagram for the CFB gasifier at Lahti, Finland

Figure 20. The CFB gasification plant at Lahti, Finland

The power plant was constructed in 1976 with a maximum power capacity of 167 MW_e and maximum district heat production of 240 MW_{th} with oil-firing. It was modified in 1982 for coal firing. A gas turbine was added in 1986 with a maximum output of 40 MW_e (at -25 °C or -77 °F). The feed rate to the plant was 163,295 metric ton/a (180,000 ton/a) (1,200 GWh/a) of coal and 800 GWh/a of natural gas.

The construction of the Lahti gasification plant was started in 1997 to replace about 15% of the total fuels burned in the main boiler with biofuels. The first switchover took place on January 14, 1998. Some specifications for this plant are shown in Table 5. The CFB gasifier produces low-Btu gas to burners in a coal-fired boiler. Hence, the fuel gas is not used directly for heat and power generation, but is rather a co-combustion process similar to the BioCoComb process under development in Austria. The boiler is a Benson-type