Appendix A
Discussion of Thermochemical Process Definitions

Certain terms relating to waste conversion have created ongoing debate, misunderstanding, or misuse among industry, government, environmental groups, and the public. For example, the chaptered version of AB 2270 (Matthews, Chapter 740, Statutes of 2002[1] contains a definition of gasification that is incomplete and therefore may unnecessarily preclude viable and perhaps preferred conversion technologies from being considered.

"Gasification" from the chaptered AB2770 (Matthews, Chapter 740, 2002);

```
SECTION 1.  Section 40117 is added to the Public Resources Code,
to
read:
40117.  "Gasification" means a technology that uses a
noncombustion thermal process to convert solid waste to a clean
burning fuel for the purpose of generating electricity, and that,
at minimum, meets all of the following criteria:

(a) The technology does not use air or oxygen in the conversion
process, except ambient air to maintain temperature control.
(b) The technology produces no discharges of air contaminants or
emissions, including greenhouse gases, as defined in subdivision
(g)
of Section 42801.1 of the Health and Safety Code.
(c) The technology produces no discharges to surface or
groundwaters of the state.
(d) The technology produces no hazardous waste.
```

In section 40117, gasification is defined as a process that produces a "clean burning fuel for the purpose of generating electricity". This is unfortunate as there are many potential products (besides electricity) that can be produced from synthesis gas. Failure to include all potential products from a gasification process in this definition inadvertently limits options for the State and waste jurisdictions and arbitrarily restricts the market. Additionally, it is unclear what is meant by "clean burning".

The subsection (a) referring to using no air or oxygen in the conversion process except to allow "ambient" air for temperature control precludes virtually all actual gasification processes if strictly interpreted. It is unclear why ambient air is allowed, but heated air is not (heating the input oxidant stream from waste heat elsewhere in the process is a common method used to improve overall energy conversion efficiency).

Also, this limits processes that utilize oxygen or other oxygen-containing synthetic gases instead of air (which may be more efficient and economic because of reduced gas flow, reactor size, and perhaps improved NO_x emissions from follow-on processes). Most gasifiers use air, steam, or pure oxygen (or a combination) in the process of converting feedstocks, such as municipal solid waste (MSW), and delivering the fuel gas to a suitable follow-on conversion system for power or chemical production.

As a preferred approach, the State should consider setting performance-based standards without restricting technology development by class rather than regulation by technology using what, in many cases may be incomplete, inaccurate, or unnecessarily restrictive definitions.

U.S. Environmental Protection Agency Definition of Gasification

Another example of a potentially limiting technical definition used in regulatory codes (if it is allowed to be applied to all wastes in general) is a proposed rule change by the U.S. Environmental Protection Agency (U.S. EPA). The rule change would narrowly define gasification in order to acceptably treat a special class of feedstocks. This concerns the U.S. EPA regulation of hazardous waste from petroleum refineries and reads in part as[2]:

```
[Federal Register: March 25, 2002 (Volume 67, Number 57)]
[Proposed Rules]
[Page 13683-13700]
From the Federal Register Online via GPO Access
[wais.access.gpo.gov]
[DOCID:fr25mr02-21]
-----------------------------------------------------------------
ENVIRONMENTAL PROTECTION AGENCY
40 CFR Parts 260 and 261
[FRL-7162-8]
RIN 2050-AE78

Regulation of Hazardous Oil-Bearing Secondary Materials From the
Petroleum Refining Industry and Other Hazardous Secondary Materials
Processed in a Gasification System To Produce Synthesis Gas

AGENCY: Environmental Protection Agency (EPA).
ACTION: Proposed rule.
------------------------------------------------------------------
Section VII-A
1. Definition of a Gasification System

Gasification system means an enclosed thermal device and associated
gas cleaning system or systems that does not meet the definition of
an incinerator or industrial furnace (found at Secs. 260.10), and
that: (1) Limits oxygen concentrations in the enclosed thermal
device to prevent the full oxidization of thermally disassociated
gaseous compounds; (2) utilizes a gas cleanup system or systems
designed to remove contaminants from the partially oxidized gas that
do not contribute to its fuel value; (3) slags inorganic feed
materials at temperatures above 2000; deg. F; (4) produces a
synthesis gas; and (5) is equipped with monitoring devices that
ensure the quality of the synthesis gas produced by the gasification
system.
```

The U.S. EPA rule change proposal is driven by the desire of petroleum refineries to be able to process oil bearing secondary (or waste) materials by gasification. Impediments now are due to classification of these secondary materials (and potential feedstocks) as hazardous wastes from the initial refinery processes that have special handling and processing requirements. By submitting petroleum refinery and other hazardous wastes to the restrictive gasification process described in the proposed rule, it is assumed that the formation of certain toxic compounds will be minimized and/or bound in essentially non-leachable vitrified ash. Refinery residues could then be considered an intermediary product/feedstock and not a hazardous waste (and regulated as such).

The proposed U.S. EPA definition of gasification system for conversion of petroleum refinery wastes requires that it operate above 2000º F in order to melt (slag) the inorganic, or ash, portion of the feedstock. This is a highly specific and restrictive subset of gasification. It should be recognized that the definition applies specifically to the narrow class of petroleum refinery wastes that are currently classified as hazardous material. The U.S. EPA gasification of refinery wastes definition, if accepted for all feedstock classes, would unnecessarily restrict development of potentially viable MSW conversion technologies.

NETL and GTC Definitions:

The DOE/NETL (National Energy Technology Laboratory) is a national laboratory funded and operated by the U.S. Department of Energy. Other DOE national laboratories are operated by contractors (University of California, Lockheed Martin, Battelle, Midwest Research Institute, Bechtel, Iowa State, etc.). NETL's primary mission is "to assure that U.S. fossil energy resources can meet increasing demand for affordable energy without compromising the quality of life for future generations of Americans."

The Gasification Technologies section of NETL is in the Coal Energy branch. The description of the gasification process used by NETL[3] is essentially the same as that found on the Gasification Technologies Council (GTC) website[4] (See ,below):

The NETL definition:

> *Gasifiers convert carbonaceous feedstock into gaseous products at high temperature and elevated pressure in the presence of oxygen and steam. Partial oxidation of the feedstock provides the heat. At operating conditions, chemical reactions occur that produce synthesis gas or "syngas," a mixture of predominantly CO and H_2.*

The Gasification Technologies Council definition:

> *Gasification technologies differ in many aspects but share certain general production characteristics. Typical raw materials used in gasification are coal, petroleum-based materials (crude oil, high sulfur fuel oil, petroleum coke, and other refinery residuals), gases, or materials that would otherwise be disposed of as waste. The feedstock reacts in the gasifier with steam and oxygen at high temperature and pressure in a reducing (oxygen-starved) atmosphere. This produces the synthesis gas, or syngas, made up primarily of carbon monoxide and hydrogen (more than 85% by volume) and smaller quantities of carbon dioxide and methane.*
>
> *The high temperature in the gasifier converts the inorganic materials in the feedstock (such as ash and metals) into a vitrified material resembling coarse sand. With some feedstocks, valuable metals are concentrated and recovered for reuse. The vitrified material, generally referred to as slag, is inert and has a variety of uses in the construction and building industries.*

This description/definition includes high pressure as a condition and temperature high enough to slag and vitrify the inorganic material. The typical feedstocks mentioned are coal and petroleum refinery wastes that are more specific than the general carbon containing feedstock. Also, it is implied that (added) steam is a necessary reactant; this is not true for a general description/definition of gasification.

A report by SAIC for the U.S. DOE/NETL[5] discusses environmental aspects of gasification-based power generation and describes a gasifier as follows:

> *The gasifier converts carbonaceous feedstock into gaseous products at high temperature and (usually) elevated pressure in the presence of oxygen and steam. Partial oxidation of the*

> *feedstock in a reducing (oxygen-starved) atmosphere provides the heat. A syngas is produced composed primarily of CO and H_2.*

This report was sponsored by the Gasification Technologies Program at NETL and the Gasification Technologies Council. It is nearly identical to the description by NETL.

The NETL/GTC gasification definition is very specific and would be inappropriate for use as a general gasification description for use in MSW conversion regulations.

General Thermochemical Definitions in the Literature

For performance-based environmental regulation, the descriptions and definitions of technologies must be accurate yet general enough so as not to inadvertently disqualify viable or promising technologies. Following are technically accurate definitions of gasification which can help inform the section of AB 2770 that defines gasification.

From the glossary of the Energy Information Administration (EIA),[6]

> *Gasification: A method for converting coal, petroleum, biomass, wastes, or other carbon-containing materials into a gas that can be burned to generate power or processed into chemicals and fuels.*
>
> *Pyrolysis: The thermal decomposition of biomass at high temperatures (greater than 400° F, or 200° C) in the absence of air. The end product of pyrolysis is a mixture of solids (char), liquids (oxygenated oils), and gases (methane, carbon monoxide, and carbon dioxide) with proportions determined by operating temperature, pressure, oxygen content, and other conditions.*

From the USDOE Energy Efficiency and Renewable Energy Glossary,[7]

> *Gasification—The process in which a solid fuel is converted into a gas; also known as pyrolytic distillation or pyrolysis.*
>
> *Pyrolysis—The transformation on a compound or material into one or more substances by heat alone (without oxidation). Often called destructive distillation. Pyrolysis of biomass is the thermal degradation of the material in the absence of reacting gases, and occurs prior to or simultaneously with gasification reactions in a gasifier. Pyrolysis products consist of gases, liquids, and char generally. The liquid fraction of pyrolysized biomass consists of an insoluble viscous tar, and pyro-ligneous acids (acetic acid, methanol, acetone, esters, aldehydes, and furfural). The distribution of pyrolysis products varies depending on the feedstock composition, heating rate, temperature, and pressure.*

The National Renewable Energy Laboratory (NREL) makes a reference to gasification[8],

> *Gasification is the thermal conversion of solid organic material to a mixture of gases (CO, H2, CO2, CH4), organic vapors, water vapor, and residual solids. Gasification of biomass takes place at elevated temperature, 700–850ºC, in an atmosphere of steam or air (or both).*

From a US Department of Energy report[9] discussing biomass gasification, (Ciferno and Marano 2002)

> *Biomass gasification is the conversion of an organically derived, carbonaceous feedstock by partial oxidation into a gaseous product, synthesis gas or "syngas," consisting primarily of hydrogen (H2) and carbon monoxide (CO), with lesser amounts of carbon dioxide (CO2), water (H2O), methane (CH4), higher hydrocarbons (C2+), and nitrogen (N2). The reactions are carried out at elevated temperatures, 500–1400ººC, and atmospheric or elevated pressures up to 33 bar (480 psia). The oxidant used can be air, pure oxygen, steam or a mixture of these gases. Air-based gasifiers typically produce a product gas containing a relatively high concentration of nitrogen with a low heating value between 4 and 6 MJ/m3 (107-161 Btu/ft3). Oxygen and steam-based gasifiers produce a product gas containing a relatively high concentration of hydrogen and CO with a heating value between 10 and 20 MJ/m3 (268-537 Btu/ft3).*

This is a general definition with no restriction on operating temperature or pressure or type of oxidant used for heat generation by partial oxidation.

From Bridgwater, 1984[10]

Gasification

-Energy is provided internally by exothermic reaction of part of the feed.
Oxygen supplies the oxidizing environment, thus

> *Air gasification*
> *-Air burns part of the feed to generate heat to gasify/pyrolyze the rest. The product contains up to 60% nitrogen. Suitable for fuel gas or ammonia synthesis, but requires complex processing to remove nitrogen for production of a carbon based chemical.*
>
> *Oxygen gasification*
> *-Air separation plant required to remove nitrogen from oxidizer (yields essentially nitrogen free product). Higher temperatures are encountered requiring better control, and higher safety standards with pure oxygen. Product is more suitable for carbon based chemical or fuels such as methanol.*
>
> *Steam gasification*
> *-Sometimes considered as a distinct category with energy supplied by a steam reforming reaction which is only exothermic at high pressures, typically above 7 bar. Common to add steam as a thermal moderator and/or reagent in oxygen gasification.*

-Relatively high temperatures can be produced.
-Usually all the carbon is converted to gaseous form leaving only an inert residue.

> *Hydropyrolysis, hydrogasification and steam pyrolysis*
> *-The use of hydrogen as a reactive gas in pyrolysis and gasification fundamentally alters the outcome of most gasification reactions. When used in combination with steam pyrolysis, the chemical kinetics of hydrogasification is enhanced at least 20 times. This feature allows wet gasification to proceed without any need for drying the feed stock. No air separation plant is needed, hydrogen is generated downstream in steam methane reformer. If Fischer-Tropsch liquid fuel synthesis reactor is incorporated, self-sustained thermal and chemical operation is possible.*

Pyrolysis

-Energy is provided externally.
-Relatively low temperatures are produced.
-Relatively low gas yields are obtained with high liquid yields and carbonaceous residues.

Liquefaction

-Energy is provided externally.
-Relatively low temperatures but high pressures are used.
-Relatively high yields of liquids are obtained.

Incineration (or Combustion)

The term ‘incineration’ in the U.S. is commonly used to mean ‘burning of waste’ (combustion of waste). The dictionary defines it as “causing to burn to ashes, to burn completely.”[11] Were this definition to strictly apply, there would be less controversy associated with the use of incineration, as complete burning would produce fewer emissions of concern.

The European Community lumps all thermal conversion technologies that utilize MSW and certain classes of other wastes under the heading of incineration (thermal treatment of wastes). EC Directive 2000/76/EC[12] contains this paragraph:

> *Article 3, paragraph. 4*
> *‘Incineration plant’ means any stationary or mobile technical unit and equipment dedicated to the thermal treatment of wastes with or without recovery of the combustion heat generated. This includes the incineration by oxidation of waste as well as other thermal treatment processes such as pyrolysis, gasification or plasma processes in so far as the substances resulting from the treatment are subsequently incinerated.*

The Directive is technology neutral and instead sets detailed limits and allowable characterizations of the emissions and residues from thermal treatment or conversion plants.

Appendix B
Cover Letter and Survey Form Sent to Vendors

To whom it may concern:
The California Integrated Waste Management Board (CIWMB) has contracted the University of California to evaluate alternative waste conversion technologies for municipal solid waste (MSW). Assembly Bill 2770 (Chapter 740, Statutes of 2002) requires the California Integrated Waste Management Board (Board) to prepare a report on new and emerging conversion technologies that might be able to use currently-disposed materials as feedstock. Further, AB 2770 requires the Board to define and describe each conversion technology; evaluate their technical performance characteristics, feedstocks, emissions, and residues; and identify the cleanest, least-polluting technologies.
The primary objective of the study is to identify and evaluate technologies (and/or processes) that may be able to reduce the amount of material being landfilled by converting post recycled MSW (or separated further if necessary) into useful products such as electricity, alternative fuels, chemical feedstocks, heat, etc. A final report documenting the evaluation will be submitted to the CIWMB at the conclusion of the project, and will most likely be available from the CIWMB web site as a contractor report and data base.
Your company was identified as a potential candidate for the evaluation of solid waste and biomass conversion technologies. In order to initiate the evaluation, we are requesting some basic information about your technology. We would appreciate if you can take a few minutes to complete the following survey:
GENERAL
What is the commercial status of your technology (commercial, pre-commercial, pilot, proposed)?
____
If applicable, what fee do you charge for your feedstock ($/ton)? ________________ What type of feedstock? ______________
If applicable, what is the current market rate for your product(s) ($/unit)? _____________ What type of product(s)? _______________________
Do you hold patents to the technology or do you license from a patent holder? If so, please provide the patent numbers.
____
If applicable, how many separate units of this technology do you or others (e.g., licensees) operate and where are they located?
____ ________
Can you please provide a short description of how the process operates (to supplement other information available to us)?
____
____
____
____
____
Does your technology currently process MSW or a component of MSW? __________
If yes, is MSW a primary or secondary feedstock? ___________I___________
Do you presently interface with a material recovery facility (MRF) to obtain your feedstock materials?
If so, which MRF and where is located? __________________________
If so, would you provide help (financial and/or hardware) to sort the type of feedstock you can best use in your conversion process? _________

If so, do you haul the feedstock from the MRF? _____ How much does it cost you to haul the feedstock from the MRF to your facility? $ ___/ton
Would you consider entering into an agreement with a MRF contractor to sort and select feed stock materials for your conversion process? __________ If so, how much would you consider paying to have a MRF contractor to sort and select from MSW materials for your conversion process? $ ____/ton
Is there any pre-processing of your MSW feedstock? For example, does the feed stock need to be dry, cut or ground to a certain size?

____

____

____

SPECIFIC
What is the design capacity and actual amount of MSW or (MSW component material) processed in TPD? ____
Please describe the quantity and type of any solid and liquid residual (process waste) output streams and how you manage or intend to manage them:

____

____

What other feedstock(s) can your technology use? Does the process require (or is it optimized for) co-feeding with these other feedstocks? If co-feeding, what are the relative amounts?

____

What is the mass reduction efficiency (see definition below) of your technology (% by wt.)? _________Alternatively, can you tell us the mass flows for your systems including feedstock, products, and all waste or byproduct streams?
What is the carbon conversion efficiency (see definition below) of your technology (% by mole)? _________Alternatively, can you tell us the elemental composition of your feedstock and the species concentrations in your products?
Can you estimate the energy conversion efficiency (see definition below) of your conversion technology (%) ? ____________
What are the ultimate products of your conversion technology and how much of each product do you generate (e.g. electricity, syngas, liquid fuels, if electricity, how big is the facility in kW or MW)?

____

What other material and energy inputs does your process require (for example, water, steam, electricity, natural gas)? Please quantify in terms of feedstock processed or converted.

____

Do you have any source emissions testing or other environmental impact data you can share with us? _____
Have you attempted to obtain permits for a conversion facility, and if so, is it now fully permitted? If not, what permits are lacking or pending?

____

Can you tell us how the facility is financed and what incentives, if any, you have been able to obtain or use?

____

Do you currently have a contractual arrangement for your feedstock with a materials recycling facility (MRF)?_____. If not, are you interested in pursuing an agreement with a MRF? ______
Do you have any promotional literature or technical documents you can share with us? __________
Please e-mail your response to Joshua Pence (jpence@cert.ucr.edu) or fax to (909) 781-5790 as soon as possible. Thank you in advance for you participation.
DEFINITIONS
MASS REDUCTION EFFICIENCY = 100% x (mass input - mass of solid waste output)/mass input)
CARBON CONVERSION EFFICIENCY = 100% x (moles carbon in output gases and oils)/(moles carbon in feedstock)

or
100%*(1- moles C in process residue/moles C in feedstock)

NOTE: Gross carbon conversion efficiency includes carbon dioxide gas in output gases. Net carbon conversion efficiency includes only those energetic carbon compounds that have a finite calorific value – please identify whether gross or net.
ENERGY CONVERSION EFFICIENCY = 100% x (calorific value or energy content of all products)/(calorific value of input feedstock)

Appendix C
List of Companies that Responded to the Survey or Provided Information on Their Technology

Company	Location	Technology
ACM Polyflow	*Akron, OH*	*Pyrolysis*
Adherent Technologies, Inc	*Albuquerque, NM*	*Catalytic Cracking*
Alcyon	*Renens, Switzerland*	*Pyrolysis*
Burbank Grease Services LLC	*DeForest, WI*	*Combustor*
Arkenol	*Irvine, CA*	*Fermentation*
Arrow Ecology	*Israel*	*Digestion*
Balboa Pacific	*New York*	*Pyrolysis*
BASSE Sambre ERI	*Moustier sur Sambre, Belgium*	*Pyrolysis*
Bioengineering Resources, Inc.	*Fayatteville, AR*	*Biochemical/Gasification*
Bioset		
BP Chemicals Ltd.	*Grangemouth, Scotland, UK*	*Pyrolysis*
Brightstar Environmental	*Wollongong, NSW, Australia*	*Pyrolysis*
Canada Composting Inc.	*Newmarket, Ontario, Canada*	*Composting/Bioprocess*
Chateau Energy, Inc. (completed by Theroux Environmental Consulting Services)	*Auburn, California*	*Plasma*
Chematur	*Karlskoga, Sweden*	*Liquefaction*
Community Power Corp.	*CO*	*Gasification*
Conrad	*Chehalis, WA*	*Pyrolysis*
Omnifuel Technologies, Inc.	*Citrus Heights, CA*	*Gasification*
Duratek	*Oak Ridge, TN*	*Stream Reforming/Pyrolysis*
Ebara-Zurich	*Zurich, Switzerland*	*Gasification*
ECN (Energy Research Institute for the Netherlands)	*Petten, Netherlands*	*Pyrolysis/Gasification*
Emery Energy Company, LLC	*Salt Lake City, UT*	*Gasification*
Energy Products of Idaho (EPI)	*Coeur d'Alene, ID*	*Gasification*
Ensyn	*Ottawa, Ontario, Canada*	*Pyrolysis*
Environmental Energy Systems, Inc.	*Oceanside, CA*	*Composting*
European Council of Vinyl Manufactures	*Brussels, Belgium*	
Europlasma	*Begles, France*	*Plasma*
Environmental Waste International (EWI)	*Ajex, Ontario, Canada*	*Pyrolysis*
FERCO	*Norcross, GA*	*Gasification*
FlexEnergy	*Mission Viejo, CA*	*Turbine Technology*
Foster Wheeler Energia Oy	*Clinton, NJ*	*Gasification*
Gas Technology Institute (GTI)	*Des Plaines, IL*	*Gasification*
Graveson Energy Management (GEM)	*Summit, NJ*	*Pyrolysis*
General Atomics	*San Diego, CA*	*Liquefaction*
Georgia Institute of Technology	*Atlanta, GA*	*Plasma*
Global Renewables		*Digestion*

Company	Location	Technology
Golden State Energy/Hawkins International	*Carson City, NV*	*Plasma*
Hebco	*Montreal, Quebec, Canada*	*Pyrolysis*
Hueristic Engineering Inc.	*Vancouver, BC, Canada*	*Gasification/Combustion*
Integrated Environmental Technologies, LLC (IET)	*Richland, WA*	*Plasma*
Improved Converters (ICI)	*Sacramento, CA*	*Gasification*
Innovative Logistics Solutions (Pyromex)	*Palm Desert, CA*	*Pyrolysis*
Intellergy Corp.	*Berkeley, CA*	*Steam/CO_2 Reforming*
International Energy Solutions	*Romoland, CA*	*Pyrolysis*
Interstate Waste Technologies, Inc. (Thermoselect)	*Malvern, PA*	*Pyrolysis/Gasification*
ISKA GmbH	*Ettlingen, Germany*	*Digestion*
JF Bioenergy	*Abbotsford, BC, Canada*	*Pyrolysis*
Masada	*Birmingham, AL*	*Fermentation*
Metso Corporation	*Helsinki, Finland*	*Upfront separation*
Minergy	*Neenah, WI*	*Pyrolysis*
Mitsui Babcock	*Renfrew, Scotland*	*Pyrolysis*
Naanovo Energy Inc		*Combustor*
North American Power Company	*Las Vegas, NV*	*Pyrolysis*
Organic Energy Systems	*Austin, TX*	*Pyrolysis*
Organic Waste Systems	*Dayton, OH*	*Composting/Bioprocess*
Pacific Northwest National Lab	*Richland, WA*	*Gasification*
Peat International, Inc.	*Northbrook, IL*	*Plasma*
Phoenix Solutions Company	*Chrystal, MN*	*Plasma*
Plas-Sep	*Ontario, Canada*	*Separation*
Plastic Energy LLC (SMUDA)	*Newvcastle, CA*	*Cracker*
Primenergy, L.L.C.		*Gasification*
PureVision Technology	*Fort Lupton, CO*	*Hydrolysis*
Recovered Energy Inc.	*Pocatello, ID*	*Plasma*
ReCycled Refuse International Ltd.	*Jersey, UK*	*Gasification*
Renewable Oil International	*Florence, AL*	*Pyrolysis*
Renewable Resources Alliance	*California*	*Gasification*
Resorption Canada Ltd. (RCL)	*Ottawa, Ontario, Canada*	*Plasma*
Serpac Environnement	*L'Arbesle Cédex, France*	*Pyrolysis/Gasification*
Solena Group	*Washington, DC*	*Plasma*
ThermoEnergy	*Little Rock, AR*	*Gasification*
Thermogenics Inc.	*Albuquerque, NM*	*Gasification*
Thide Environnement	*Voisins Le Bretonneux, France*	*Pyrolysis*
Torftech	*Berkshire, UK*	*Gasification*
Uhde - ThyssenKrupp	*Dortmund, Germany*	*Gasification*

Company	Location	Technology
WasteGen UK	*Gloucestershire, UK*	*Pyrolysis*
Westinghouse Plasma Corp.	*Madison, PA*	*Plasma*
Yolo County Landfill	*Woodland, California*	*Digestion*

Appendix D
Descriptions of Pyrolysis Processes

The following appendix provides descriptions of specific technologies that utilize either pyrolysis or pyrolysis in combination with a post-combustion system. A listing of these technologies is provided in Table D-1. Although the focus of this report is on MSW, additional technologies processing other wastes are also listed since they could potentially be utilized with MSW also. Due to the differences in feedstocks, some modification in these technologies might be required prior to use for MSW.

Table D-1. Commercial, Demonstrated, and Actively Promoted Pyrolysis Technologies

Company	# of Facilities	Scale (TPD)	Principal Facilities	Fuel(s)
Municipal Solid Waste				
Commercial				
Waste Gen UK, Technip	2	120	Burgau, New Namm, Germany	MSW, mixed waste
Thide-Eddith	3	30-140	Japan, France	MSW, industrial
Siemens/Takuma/Mitsui	7	130-440	Japan	MSW
Semi-commercial				
GEM Gas Conversion	1 demo	40	UK	MSW, Industrial waste, Sewage
International Energy Solutions	1	50	Romoland, CA	Pretreated medical waste, electronic waste, fireworks + sewage sludge
Pyromex	2 operating, 2 planned	25-400	Germany, California	Sludge, greenwaste, ASR
Demonstration Plants				
Balboa Pacific	3	50	California, Dom Rep, Mex	Various wastes
Conrad	2	2-24	Chehalis, WA	Tires
Nexus	1 pilot/1 planned	10-100	France	MSW, RDF, non-haz. industrial waste
North America Power Company	1	12	Las Vegas, NV	Tire, MSW, industrial, medical
Serpac Pyroflam	1	26	France	Mixed waste, MSW, industrial and hospital waste
Von Roll	1	144	Bremerhaven, Germany	MSW, residual waste from recycling, ASR
Wood / Ag. Waste				
Ensyn Technologies	4 operational/2 planned	1-40	Wisconsin, Canada	Wood, petroleum
Dynamotive	3 pilot, 1 planned	2-50	Canada	Wood & ag. waste
BTG Biomass Technologies	1 demo/1 planned	1-7	Netherlands, China	Wood
Renewable Oil International	1 pilot/1 planned	5-15	Russelville, AL & MA	Chicken litter, wood
JFBioEnergy	1 demo	120	Washington	Wood, manure, MSW

Company	# of Facilities	Scale (TPD)	Principal Facilities	Fuel(s)
Tires				
BPI Technologies	1 demo, 1 com planned	35-220	UK, Denmark	Tires
Environmental Waste International				Tires
Sludges				
NESA	3	N/A	Germany, France	Biosolids, industry waste, sludges
Pilot Scale / Demonstration				
ACM Polyflow	1 planned	240		Polymers
Ambient RGR	1	400 kg/hr	Bergamo, Italy	RDF, Tires, carpet
Hebco International				
Traidec	1 sold, 1 design	12	Mexico	Industrial waste/sludge
Not Active				
Andre Scientific	design	100 tire/hr		Tires
Beven Recycling	1 reference	1-2	Witney, UK	Tires
Pyrovac				
Weidleplan		80	Miltzow, Germany	Tires

Pyrolysis of MSW

The companies under this category have all developed processes that are either being currently used for MSW as a primary feedstock or are designed to do so.

Commercial

The companies in this category have one or more commercial units that have been commissioned and have been operating for a sufficient period of time to confirm satisfactory operation.

Mitsui/Takuma/Siemens [13,14,15]

The "Schwel-Brenn Verfahren" process (or "Thermal Waste Recycling Process") was marketed by Siemens in Europe in the mid- to late 1990s and is now marketed by Takuma and Mitsui in Japan.

The basic process combines pyrolysis with high-temperature combustion and can be utilized with MSW, sewage sludge, or ASR. The system utilizes a horizontal reactor where the waste is pyrolyzed at 840^{o} F for about one hour. The produced pyrolytic gases are then burned along with the pyrolytic char/dust in a combustion chamber that operates at 2370^{o} F. The energy produced in the combustion chamber is used to raise steam to 750^{o} F for electrical production. The temperatures used in the combustion chamber are sufficiently high to fuse the inert ash into a slag. This slag can subsequently be used for road construction applications. Juniper Consultancy Services conducted an analysis on this system and found that approximately 405 KWh could be formed per ton of waste. This corresponds to an efficiency of approximately 17%.

Although originally active in Europe, Siemens experienced considerable problems with the continuous operation of its Fürth Plant in Germany that culminated in a serious accident at the site. The accident was reportedly due to a plug of waste that formed in the pyrolysis chamber. This resulted in overpressurization and escape of pyrolysis gas. Some plant personnel were hospitalized and other people in the surrounding community were also admitted for observation. According to European sources, one of the main causes of the accident was poor feedstock preparation in that the unit did not utilize shredding and was accepting items as large as a full mattress with springs. A 440 lb per hour pilot plant was also operated in Ulm-Wiblingen, Germany, since being commissioned in 1988. As a result of the problems with the Fürth plant, Siemens eventually withdrew from the market beginning in 1999.

The original Siemens process appears to be more successfully applied in Japan by license holder Mitsui Babcock and Takuma. Mitsui Babcock currently has six active installations processing between 150 and 450 tons per day (TPD). This includes one facility that has operated since 2000; the other facilities have been in place for at least a year. Mitsui Babcock incorporated several design upgrades on the Siemens design, including the shredding of waste to be processed and a different sealing mechanism for the pyrolysis drum, which should avoid the previous issues found at the Fürth facility. The system is marketed under the name of "Recycle 21" or R21. A listing of the individual facilities for Mitsui Babcock is provided in Table D-2. The emissions for these facilities are also provided in Chapter 5 on environmental impacts.

Licensee Takuma also has several facilities in operation. A 99 TPD ASR processing plant has been operating in Fukuoka for the Kanemura Co. Ltd since 1998. A 179 TPD facility for processing MSW has been operating for approximately one year in KoKubu City, Japan. One other facility is processing MSW at 133 TPD in Oshima, Hokkaido Island, Japan.

Table D-2. Mitsui Engineering and Shipbuilding—Commercial R21 contracts in Japan

Contract/Location	Contract Award Date	Contract Completion Date	MSW Capacity
Yame Seibu Regional Co-operative Fukuoka Prefecture	July 1997	March 2000	2 x 121 tons per day 55 tons per day bulky waste facility
Toyohashi City Aichi Prefecture	September 1998	March 2002	2 x 220 tons per day 77 tons per day bulky waste facility
Ebetsu City Hokkaido Prefecture	September 2000	November 2002	2 x 77 tons per day 38 tons per day bulky waste facility
Koga Seibu Regional Co-operative Fukuoka Prefecture	November 2000	January 2003	2 x 143 tons per day No bulky waste facility
Nishi Iburi Regional Co-operative Hokkaido Prefecture	January 2001	March 2003	2 x 115 tons per day 63 tons per day bulky waste facility
Kyouhoku Regional Co-operative Yamanashi Prefecture	March 2001	January 2003	2 x 88 tons per day No bulky waste facility

WasteGen UK, Technip [16,17,18,19] *[Provided information on technology]*

WasteGen UK is marketing “Materials and Energy Recovery Plants” (MERPS). This company seems to be the inheritor of rotary kiln pyrolyzer technology developed by PLEQ, a now-defunct East German company, and then the Technip division of the Mannesmann company. Franz-Eicke von Christen is the technical director for the company. He was a founder and director of the original PLEQ company. Technip is operating separately and appears to be promoting this same technology.

A full-scale unit has been operating in Burgau, Germany, since 1987. This site is presented on the WasteGen UK website, but was originally developed while von Christen was at Technip. The plant is operated by the municipality. The plant processes a mixture of MSW, industrial waste, and sewage sludge. The MSW is not sorted prior to processing but is shredded to <12 in and mixed with the sewage sludge. The waste is transported between the storage bins and the feeding hopper using a crane. The facility uses two rotary kilns, 66 ft long by 7.2 ft diameter.

Each processing line is capable of 3 ton per hour. Some 40,000 tons per year of waste material is pyrolyzed at the facility. The kilns are heated by combustion of a portion of the pyrolytic gas. The outer surface of the kiln is heated to 1020^{o} F resulting in a temperature of 840–880^{o}F in the reaction zone, which is operated at a slight vacuum. The residence time in the reactor ranges from 30 minutes to two hours; one hour is typical. The drying of the waste takes place in the initial portion of the kiln. Lifting blades are also provided in the front part of the kiln to facilitate mixing of the feedstock in the kiln. Quicklime is added to the feedstock material in the reactor to help control HCl, HF, and SO_2 emissions, resulting in a relatively clean product gas.

The pyrolysis gas is fed into a combustion chamber where it is combusted at a temperature of nearly 2,200^{o} F in excess oxygen of 5% to 8%. Since the combustion temperature is higher than that typically used for incineration, the levels of CO, hydrocarbons, dioxins, and furans are reduced to levels such that no further treatment of these pollutants is required. A portion of the flue gases is also recirculated to the combustion chamber to reduce NO_x emissions. Typical daily average emissions results for this facility are included in Chapter 5. A portion of the energy from the combustion process is recirculated to heat the pyrolysis chamber while the remaining energy is used in a boiler to raise steam for a 2.2 MWe turbine/generator.

The solid residues from the pyrolysis reactor are discharged via a water quenching process. The ferrous metals are recovered using an overhead magnetic separator for recycling. The remaining pyrolysis coke is then combined with the dust and fly ash from the bag house gas cleaning system and transported to landfill.

The energy recovery of this system was analyzed to be 427 KWh/ton, which corresponds to an efficiency of approximately 18% for a 10 MJ/kg input feedstock material. On a mass basis, 12% is recovered as recyclable metal and 21% (pyrolysis char and fly ash) is sent to landfill.

Technip also has a second facility northeast of Dortmund at Hamm in Germany that has been operating since 2002 with a capacity of 110,000 ton per year with two streams of 7.3 ton per hour. Technip is informally working with Duratek to incorporate a large-scale steam reforming plant at this facility.

Semi-Commercial

Companies/technologies at several different levels are included in the semi-commercial category. This includes companies that are in the processes of commissioning a full commercial plant, companies that are operating plants with relatively small capacities on a full-time basis, and companies that have conducted a pilot-scale demonstration and have secured orders for further full-scale plants.

International Environmental Solutions [20] (Romoland, CA)[Provided survey and supplementary materials]

International Environmental Solutions (IES) is currently in the process of commissioning a 50 TPD facility in Romoland, California, based on pyrolysis technology. The IES process applies high temperatures (1200^o F to 1800^o F) indirectly to a retort chamber, which houses an environment free of flame and oxygen. Inside, the hydrocarbons and other waste components are converted into gases and basic elemental solids via destructive distillation and molecular decomposition. All off-gasses are diverted to a thermal oxidizer operating at 2200^o F+ for conversion to carbon dioxide, oxygen, and water vapor. The solid residues of the waste stream are passed out of the retort as carbon, sterile sands and/or fixed, non-leachable metals.

The IES facility obtained a construction permit from the South Coast Air Quality Management District (SCAQMD) and is now performing tests necessary to show it meets agency requirements. Testing includes a variety of waste streams including, but not limited to: biosolids, MSW, fireworks, infested forest trees, and tires. Initially targeted wastes include medical waste, electronic waste, and fireworks with infested forest tree bark.

Waste heat at the Romoland facility will be used to generate electricity for use on-site as well as to power a wastewater treatment facility constructed at the site. Power will be adequate to meet all site needs. Future IES systems will be larger and will provide electricity for off-site sale or use.

The IES facility is constructed pursuant to proprietary patents and patent applications currently on file both in the USA and abroad.

Balboa Pacific Corporation and Balboa Energy Technologies, Inc. [21,22] (New York) [Provided supplementary materials]

Balboa Pacific has developed a pyrolysis with gasification process that is called the Bal-Pac Thermal Converter. The process uses a combination of pyrolysis and gasification and can be used for a variety of waste streams including medical waste, fireworks, MSW, dried sewage sludge, tires, and MSW. After any necessary drying and preprocessing, the waste is introduced into a rotary drum pyrolysis reactor that operates between 1000–1800^o F. The waste is introduced to the pyrolysis reactor using a combination of an auger screw feeder and a dual air lock system. The char is discharged after the pyrolysis reactor and can subsequently be marketed as carbon black. The pyrolysis gases are directed into a thermal oxidizer that operates between 1600–2200^o F. The flue gases from the thermal oxidizer are then used to generate steam for a waste boiler.

The initial application of the Bal-Pac technology was a pilot scale 2.5 TPD demonstration unit. This unit operated for more than seven years in Long Beach, California, and completed approximately 1,000 demonstration runs during that period. Balboa Pacific is currently constructing one 150 TPD unit in the Dominican Republic and one 150 TPD unit in Mexico. Balboa Energy Technologies Inc has also issued a license to The Sipprelle Investment Group of Long Beach, which is planning to construct a facility.

Graveson Energy Management (Summit, NJ) [23,24] [Survey and other information provided]

Graveson Energy Management (GEM) has developed a process similar to fast pyrolysis that it calls thermal cracking. The technology can be used for the disposal of various organic wastes including MSW, industrial wastes, wood waste, waste oils, sewage sludge, and tires. The feedstock material is gravity fed continuously via a centrifuge into the combustion chamber. The feedstock should be dried to a moisture content of less than 10% and sized to 4 mm to provide optimal efficiency. The reactor chamber itself is a vertically mounted, cyclonic vessel surrounded by a layer of insulation. The gas burners heat the outer wall to 1560^{o}F to provide the temperatures necessary for the pyrolysis reactions in the reactor. The reactor itself is a fast pyrolysis system where the shredded waste is subjected to extremely high heating rates in the absence of oxygen to provide rapid volatilization into a gaseous product. These gases are immediately piped into a blast cooler where they are rapidly cooled. The gas product can subsequently be converted to electricity. The typical composition of the reactor product gases is provided in Chapter 4.

GEM operated a commercial size 36 TPD unit in South Wales from 2000 to 2002 for the processing of MSW. The unit in South Wales was planned for expansion from 1.5 ton per hour (TPH) to 6 TPH, but financial issues for the operator have currently put this project in limbo. As part of the approval process for the South Wales facility, an independent outside laboratory performed analyses of waste, raw gas, char, and combustion gas. This facility uses an autoclave as part of the up-front processing that caused some problems in the handling of the waste. Emissions and ash content values for this facility are provided in Chapter 5.

Orders for six units have been secured and are in various stages of planning, including two in the U.K., one in the U.S., one in Spain, one in Canada, and a second in a discussion stage in Canada. A different feedstock handling system is planned for future orders that will incorporate magnetic separation of metals and a shaker table to separate other inorganics prior to shredding followed by an additional magnetic separator. GEM has also operated a 0.5 TPH prototype unit for testing since 1998.

North American Power Company [25] (Las Vegas, NV) [provided survey and supplemental information]

North American Power Company has developed a pyrolysis unit dubbed the Thermal Recovery Unit (TRU). The TRU is a pyrolysis unit followed by a thermal oxidizer. Organic material (hazardous and non-hazardous) is sorted and shredded to a 1” or 2” particle size. It is also dried to moisture content of 20% or less. Feedstocks include: tires, plastics, woods, soils, municipal, industrial, and medical wastes, pesticides, oil field sludge, and polychlorinated biphenyls (PCB)- contaminated materials.

North American Power currently has a facility with two TRU systems running in Las Vegas, Nevada. This facility has processed 1,000 lbs. of material per hour over a 16-hour-per-day, 5-day-a-week operation. The Las Vegas facility is currently using regenerate activated carbon, which is the primary ingredient in most modern air and water filtration systems. Although the facility is not currently using MSW, it is believed the facility does have this capability. The close proximity to the California border also merits attention.

At the Las Vegas facility, dried and shredded material is continuously fed at 500 lbs per hour to each TRU through an airlock system that feeds the retort chamber. The process can handle any form of flow, whether liquid, slurry, sludge, or solid. The material stays in the retort chamber, which is maintained at 1000–1850^{o} F until a sufficient amount of the material has been converted to gas, typically a 35- to 45-minute process. At that point, the gases are transferred to the thermal oxidizer. Here the gases are combined with oxygen, ignited, and raised to 1600–2250^{o} F. At these temperatures, toxic and noxious emissions are eliminated. The retention time for the gases in the thermal oxidizer is approximately two seconds.

With this system, a 95% reduction of the volume going to a landfill can be realized. Therefore, the excess material coming from the retort, both sterile and non-leachable, can be as little as 5% of the initial waste stream fed into the air lock.

According to North American Power Company, the emissions have been shown to meet and surpass the standards set forth by the U.S. EPA. These regulations include, but are not limited to: the Toxic Substance Control Act, the Resource Conservation Recovery Act, and the Clean Air Act. Furthermore, the volatile organic compound (VOC) Destruction Removal Efficiency of 99.9% has been achieved. Due to the emission dependence on the waste stream content, it may be required to fit a wet or a dry scrubber on the stack to ensure that the regulation requirements are met.

PYROMEX—ILS Inc. [This company provided us with a survey and literature concerning its process.]

Starting in 1989, Pyromex successfully implemented its technology into the European market, developing its waste neutralization systems, its pyrolysis technology, and its patented “ultra-high temperature gasification” system. This system, operating between 1832°F and 3100°F, converts the “pyro” gas coming from the retort into an energetic mix of selected gases, with synthesis gas (H_2 and CO) making up the largest fraction at around 70% by volume. The main product of the Pyromex technology is energy, with some mention of the inert basalt material from the gasification chamber, as well as the recyclable material, having some market value. Pyromex reports that the energy available from the “pyro” gas, after the plant’s own use of energy, is approximately 600 kWh/ton.

Pyromex has a 25 TPD facility that was commissioned in Emmerich, Germany, in February 2002 for sludge treatment and has been operating continuously since then. Another 25 TPD sludge treatment facility was planned for commissioning in Neustadt a.d.W., Germany, in May 2004. The plant operating in Germany is set up to pretreat the incoming waste to glean whatever recyclables are in the mix, to obtain a moisture content between 20 and 30%, and to shred the material to an appropriate size for the reactor feed line. The processed material is then fed unto the retort. (The retort/gasification systems available run between 10 to 500 TPD, with the option of adding auxiliary 25 TPD reactors to increase the daily processing capability.)

Pyromex is represented in North America by Innovative Logistics Solutions, Inc. A 400 TPD ASR processing system is being developed at Adams Steel in Anaheim. A 250 TPD greenwaste processing facility is also being developed at SoCal Greenwaste in Thousand Palms. These two California projects are scheduled to begin in August and September of 2004, respectively.

Addressing the environmental impacts of its technology, ILS maintains that it meets and surpasses the German regulations for air pollution prevention, as well as meeting the emission limits set forth by China, the EU, Japan, the U.K., and the U.S. EPA. Pyromex A.G. holds several patents internationally (Australia, Bulgaria, Czechoslovakia, Iceland, Israel, Latvia, Malta, Russia, Slovak, Slovenia, Turkey, U.S., U.K.) and has patents pending in additional countries (Canada, China, India, Japan, Mexico, South Korea).

Thide Environmental (Voisins Le Bretonneux, France) [26,27,28] [Provided Supplementary Information]

The EDDITh process was developed by Thide Environment S.A. of France and the Institute Francais du Pétrol (IFP). The process is based on a rotating drum pyrolysis scheme. Following materials sorting and drying, the material is conveyed into the rotating pyrolysis drum. The material is pyrolyzed at a temperature of 840–1020^{o} F with a residence time of approximately 30 minutes. The producer gas is burned at 2010^{o} F to provide the heat for the pyrolyzer and process steam for drying. To reduce emissions, a low-NO_x burner is used in the combustion chamber.

Thide seems to be trying to market the solid residue char as a solid fuel for use off-site. The coke-like by-product is being marketed under the trademark CARBOR. Thide claims the char can be washed and separated from the metals, other inerts, and soluble salts. Even if washing the char is effective, it seems that it would be costly and energy intensive, possibly making it unattractive as an off site solid fuel. Thide reports that the solids output (in % of input material mass) is 4% is recyclable metal, 10% ash, and 23% washed char.

Thide-Environmental has a 50,000-ton-per-year (TPY) facility in the town of Arras, France, that is beginning full operation May of 2004.[29,30,31] Thide has a 0.8 TPH pilot plant in Vernouillet, France, that accumulated approximately one year's worth of operating experience since its construction in 1992. Thide Environmental also has licensed its process to Hitachi for Japan.[32,33,34] It has a plant in L'usine d'Itoigawa, Japan, with a capacity of 25,000 TPY that has been operating since May 2002 and a plant in Izumo, Japan, with a capacity of 70,000 TPY that has been operating since May 2003. It also has a 1 TPH pilot plant that has accumulated 5,000 hours of operation since 1999.

Pilot or Demonstration Scale

The companies in this category have demonstrated their technology at a pilot scale level and are in the process of moving to a more commercial scale or are actively seeking opportunities to move to a more commercial scale.

Conrad Industries, Inc. (Chehalis, Washington) [35,36,37] [Company provided supplementary information]

Conrad Industries, Inc., has developed a pyrolysis process that can be utilized for the thermal conversion of various organic wastes into gas, oil, and carbon products. The system is called the Advanced Recycling Technology (ART) process. The system is designed for use with feedstocks shredded to 2" with a moisture content of 15% or less. The reactor is a horizontal unit and feedstock enters via a rotary air lock and a screw feeder. The solid products from the reaction vessel are transferred to the classifier for separation. The exiting gas stream is drawn into a condensing system for oil recovery.

The remaining non-condensable gas fuels can be used in burners to maintain process temperatures or for use in other energy recovery systems. Juniper Consultancy Services indicates that information about combustion gas cleaning is not available, although none may be utilized due to the small gas volumes. Calcium hydroxide can be added with the input feedstock however, to react with HCl as it forms in the pyrolysis reactor.

The company provided operational data for tires and some additional data for plastics. For tires, the material balance for the system output included 36% pyrolysis oil, 32% fixed carbon, 21% non-condensable pyrolysis gases, 8% steel and fiberglass, and 3% water. Based on 1 TPH of tires, it was indicated that the system energy input would be approximately 33 million BTU/hr, with an energy output of 8 million Btu/hr in pyrolysis gases, 13 million Btu/hr in pyrolysis oil, and 8 million Btu/hr in carbon char.

Two pilot-scale demonstration plants with capacities of 3.5 and 24 TPD have been constructed and tested in Chehalis, Washington. The ART system can be designed in modules of 24, 48, and 72 TPD capacities.

Conrad Industries has also conducted a three year study with the American Plastics Council to demonstrate the conversion of post-use plastics into liquid petrochemical feed stocks.

Nexus Softer Process [38](Châteaurenard Cedex, France)

Nexus has refined a pyrolysis process originally developed by the Societe Francaise de thermolyse. The process uses a rotary kiln reaction chamber and can be used to process MSW, tires, and non-hazardous waste. The process uses open-top containers to transfer the waste feedstock to the kiln. The containers are introduced into the kiln through an airlock isolation system to eliminate oxygen in the process. After processing, the containers are removed from the kiln through another set airlocks. The waste is heated to the pyrolysis temperature of 1200^{o} F by passing hot flue gases through the base of the containers. The pyrolysis reaction varies in length of time, but can take up to 8 hours for higher moisture feedstocks. The char remaining in the container is tipped out after the container exits the kiln and is transferred back to the container filling area.

Nexus developed a pilot laboratory in 1993 and a larger scale demonstration plant of 5,500 ton per year near Avignon, France, in 1995. Nexus had announced or has begun to build several plants in various regions of France, including two 33,000-ton-per-year facilities and two tire facilities. Subsequent to these announcements, Nexus was put under court administration.

SERPAC Pyroflam Process (L'Arbresle Cédex, France) [39,40,41]

The P.I.T. Pyroflam process was developed by BS Engineering S.A. affiliate SERPAC Environment of France. The Pyroflam process is designed for use with mixtures of solid wastes with sewage or other sludges. The process utilizes a horizontal reactor that incorporates both a pyrolysis chamber and a subsequent combustion chamber. The pyrolysis reactor operates at 1110-1290^{o} F. The resulting char and pyrolysis gas then continue to a combustion chamber that operates at about 1470^{o} F with the injection of substoichiometric amounts of oxygen. The producer gases from the pyrolysis and char combustion flow counter-current in the reactor.

These producer gases are then recovered through a boiler, where combustion at 2010–2190^{o}F occurs in the presence of 6% oxygen. The non-combustible ash then leaves the horizontal reactor at the end for disposal. Material/energy balance for the processes indicates that for a 9.2 MJ/kg input feedstock and an input of 35–70 KWh/ton, an electrical output of 400–470 KWh/ton is achieved. Typical process emissions are provided in Chapter 5. Dry scrubbing techniques are used for emissions control, eliminating liquid by-products. Serpac operated a 26 TPD demonstrator unit located at the Budapest airport from 1996 to 2003. Serpac has installed a new 45 TPD facility in Keflavic, Iceland, that is scheduled to begin operation shortly.

Von Roll RCP (Zürich, Switzerland) [42,43]

Von Roll has a long history of utilizing conventional moving grate technology for MSW dating back to the 1930s. The Recycled Clean Product (RCP) process is a moving grate and melting process that has been used for applications with MSW, residual waste from recycling, and ASR. The RCP process is essentially a three-step process including a grate-type pyrolysis chamber, a smelting/Holderbank-Smelt-Redox (HSR) furnace, and a circulating fluidized bed reactor. The reactor for the process is a reciprocating grate furnace that operates at a bed temperature of approximately 930^{o}F. After pyrolysis, the pyrolysis coke and any unused pyrolysis gas are drawn into a smelting furnace, where high temperatures and additional oxygen are used to melt all solid materials. The gases remaining from the smelting furnace are then combusted in a circulating fluidized bed boiler at temperatures below 1830^{o} F.

A demonstration plant using the RCP technology was installed and began operations in Bremerhaven, Germany. Although the moving grate furnace and smelting technologies are well known technologies, several years were required to bring the Bremerhaven facility up to full operation. Combining the different technologies does add to the complexity of the system. Since 1997, the plant was able to increase production processing to approximately 4,900 tons of material in 1999 and 8,600 tons of material in 2000. A 50,000 TPY per year ASR-fueled plant is also planned for Switzerland.

Pyrolysis of Wood/Agricultural Waste into Liquid Fuels

To date, the use of biomass waste-to-energy facilities is one of the important options in the disposal of biomass and production of electricity in California. An alternative process for the use of waste-to-energy facilities could be pyrolysis for the production of liquid fuels. The process of pyrolysis for the processing of biomass into liquid fuels has been developing over the past 10–15 years. Some of the first demonstration/pilot plants were built in Europe in the mid- to late 1980s.

This includes a plant by Alternative Energy Technologies (Alten) in Italy and by Bio-Alternative in Switzerland. Several other pilot plants were constructed in the early- to mid- 1990s in Europe, including a plant constructed by Union Fenosa in Spain, a plant constructed by Egemin in Belguim, and a plant purchased and installed in Bastardo, Italy, by ENEL.

A number of other pilot or research programs in this area were also sponsored under European programs, such as the JOULE or FAIR programs.. This subsection includes profiles of some of the more prominent North American companies currently developing commercial biomass fast pyrolysis processes. While these processes are generally designed for wood waste, some of these them could also be modified to process MSW.

Commercial

Ensyn (Boston, Massachusetts) [44,45] [provided survey and other information]

Ensyn has a Rapid Thermal Processing (RTP) technology that uses a fast thermal conversion process that takes place at moderate temperatures and atmospheric pressures. The process uses a continuous stream of hot sand to supply heat to the process. The liquid bio-oil is recovered when the intermediate vapor phase is quickly cooled. The resulting products depend on the feedstock, but a typical distribution for biomass is bio-oil (75%), non condensable gases (12%), and char (13%). These products are then converted to either energy or valuable products. The final ash percentage depends on the feedstock with 1%-2% ash for wood and 8%-10% ash for grass.

The feedstocks currently utilized include wood, paper, bagasse, corn fiber, and other biomass products. The feedstock is ground to less than ¼" and dried to less than 8% moisture prior to processing. The technology currently does not utilize MSW but could be adapted to MSW or other carbonaceous feedstocks.

Ensyn currently has six operating units in Ontario, Canada, and Wisconsin with two others under construction. The units range in size from 40 to 70 TPD but could be made larger. The RTP technology can also be applied to the processing of heavy crude oil components into light more valuable components, and a commercial demonstration facility of this type is currently being built in conjunction with Ivanhoe Energy near Bakersfield, California.

Dynamotive Biotherm Process [46,47] [Vancouver, BC, Canada]

Dynamotive has developed a pyrolysis process that is used primary to convert wood and agricultural waste to pyrolytic oil for fuel and char for activated carbon. The process is based on a process originally developed by Resource Transformations International Ltd., which was formed in conjunction with researchers from the University of Waterloo in Ontario, Canada. The process uses a fluidized bed for the pyrolytic reactor that operates at a temperature of 840–930^{o}F. Waste is shredded and dried prior to entering the reactor. After the reactor a cyclone is used to separate out particulate matter and the remaining gases are then condensed into the oil product. The process produces approximately 65-75% bio-oil, 10-15% gas, and 10-25% inorganic char. Dynamotive has two plants in Canada with capacities of 2 and 14 TPD. A third 110 TPD facility is in the final stages of construction and planned for commissioning in fall of 2004 at the Erie Flooring and Wood Products plant in West Lorne, Ontario. The bio-oil from this facility will be used to fuel a gas turbine developed by Magellan Aerospace, Orenda Division, to produce up to 2.5 MWe of electricity.

Renewable Oil International [48] (Florence, AL) [provided survey and other information]

Renewable Oil International has developed a fast pyrolysis thermochemical conversion system of carbonaceous wastes. The primary feedstocks for the process are currently chicken litter and wood waste. Similar to other fast pyrolysis processes, the waste is heated in an oxygen-free environment to produce liquid and gaseous by-products. The feedstock is dried as needed and shredded to a size of about 1/8 inch. The primary marketable product is the bio-oil. Renewable Oil International currently has a 5 TPD plant in Russellville, Alabama, and is currently designing a 15 TPD facility for installation in Massachusetts.

BTG Biomass Technologies (Netherlands) [49,50]

BTG has developed a flash pyrolysis process based on a design originally developed at the University of Twente. The BTG process is aimed at the processing of wood-based feedstocks into bio-oil. Organic materials that have been tested at their pilot plant include bagasse, palm residues, rice and olive husks, straw, ASR, dried sludges, and different types of wood. The requirements for the feedstock are that it is sized to <6 mm and has a moisture content <10wt%. The process utilizes a rotating cone reactor, with the feedstock and sand introduced at the bottom of the reactor. The resulting centrifugal force moves the particles upward, where flash heating occurs. According to BTG claims, the resultant products are 79 wt% bio-oil and 10 wt% char and gas. BTG has provided a 110-lb-per-hour unit to China for testing and has tested using a 550 lb/h facility since the late 1990s. On its website, BTG indicates that a 50 TPD facility was planned for construction and commissioning in 2003. BTG also indicates that it has a gasification test bed capable of processing up to 25 kg of materials per hour.

JF BioEnergy Inc. (British Columbia, Canada)[51] [provided survey and other information]

JF BioEnergy has developed a pyrolysis process that can be used with a full range of organic feedstocks. Their primary feedstock focus is on wood waste, factory farm manure, and MSW. Prior to processing, the feedstock is shredded to <3 in. Any moisture levels below 40% are acceptable for the process. The process is currently patent pending. The pyrolysis units will have 18 air absent retorts extending through an 18 x 14 x 20 ft high steel reactor lined with 4 inches of refractory. The retorts are stainless steel pipes that serve as jackets that convey by augers the organic material through the reactor at high temperatures, thus producing charcoal. While the residues are conveyed through the retorts, gases are exhausted through a series of vents and past a condenser. The condensable gasses are converted into bio-oil that is captured into holding tanks. The noncondensible gases are returned to the reactor and are used as process fuel. This eliminates the need for external fossil fuel except for start-up. The unit is designed to process up to 120 wet TPD.

JF BioEnergy Inc. has applied for a permit to conduct a three-month pilot project for a 12-TPD facility at a dairy farm in Sumas, Washington. The facility will convert cow manure and some wood waste into charcoal. The dairy farm and another farm close by generate approximately 100–120 wet TPD of cow manure from 4,000 cows. The permit process is being reviewed by the North West Air Pollution Authority in Washington State. Expansion will depend upon success of the pilot and a sale of the technology.

Pyrolysis of Sludge Waste Processes

The companies under this category have all developed processes that are either being currently used for sewage or other industrial sludges as a primary feedstock or are designed to do so. It is anticipated that some of these processes could be modified to process MSW.

Commercial

The companies in this category have one or more commercial units that have been commissioned and have been operating for a sufficient period of time to confirm satisfactory operation.

Nesa [52](Luvain La Neuve, Belgium)

Nesa is a Belgian company and a division of UM Engineering, one of the leading metals companies in the world. Nesa has been operating thermal processing units at three locations for a number of years. This includes two plants operating in Zanders, Germany, for the disposal of paper mill sludge operating from 1978 and 1990, respectively. A third plant located in Ciments D'Origny, France, has been operating since 1999 for the disposal of industrial sludge. The process is based on the Nichols-Herreschoff multiple hearth furnace. Although the multiple hearth technology has been superseded for many biosolid and industrial sludge applications, it is still a well-proven technology that has been used for many years for the incineration of biosolids from water treatment. The process includes seven separate hearths and includes a drying step, a pyrolysis step, and subsequent combustion. The pyrolysis steps occur in hearths with temperatures ranging from 930–1110^{o} F. The producer gases are subsequently combusted at temperatures in excess of 1470^{o} F.

Semi-Commercial

The companies in this category are in the process of commissioning a fully commercial plant.

ESI Enersludge Process [53](Burswood, WA, Australia)

Environmental Solutions International Ltd (ESI) currently owns the rights to a process called the Enersludge process, which originally was developed at the Tubingen University in Germany. The Enersludge process is a pyrolysis technique that is applicable for use with sewage and other organic sludges. The system utilizes a dual reactor design. In the first chamber, the sludge is volatilized at 840^{o} F. The resultant gases and char are then reacted in a second reactor to produce a bio-oil product. Any remaining gaseous and char components are then combusted in a gas generator to provide thermal energy for the drying process. A commercial scale Enersludge plant was commissioned in October 2000 at the

Subiaco waste Water Treatment Plant in Perth, Australia. This plant is designed to process 28 TPD of sludge. ESI has also licensed the technology to Mitsubishi Electric in Japan, and these two companies jointly designed a pilot plant in Osaka, Japan.

Pyrolysis of Used Tires

The companies under this category have all developed processes that are either being currently used for used tires as a primary feedstock or are designed to do so. It is anticipated that some of these processes could be modified to process MSW.

Semi-Commercial

The companies in this category are in the process of commissioning a fully commercial plant.

BPI Projects (Manchester, UK) [54]

BPI projects has developed a pyrolysis process for used tires. The process is based on a chain grate furnace. The producer gas produced is subsequently combusted in a waste heat boiler to generate steam that can be used as a heat source or to generate electricity. The technology is being marketed by Energy Power Resources, a UK project developer. EPR has built a 12,000 TPY demonstration plant in Denmark that has been operating since the end of July 2001. Construction on a second plant was scheduled to begin in 2001. This plant is to be located near Wolverhampton, U.K., and is expected to be on line in 2003. The plant will have a capacity of 65,000 TPY of tires and will generate 15.5 MW of electricity. Financing for this plant is being provided by the European Development Fund.

Environmental Waste International (Ajax, Ontario) [55,56] [provided survey and other information]

EWI manufactures and markets systems that use microwave heating to pyrolyze the feedstock in an inert or low-oxygen atmosphere. The basic process is like pyrolysis with standard volatile gases, tars, and char as the products (relative amounts and compositions are feedstock dependant).

The company is focusing on used tires and biomedical waste as the primary feedstocks for its commercialization efforts. These feedstocks were selected after a series of technological, economic, and market studies. Other potential feedstocks include chemical sludge, ASR, and animal wastes. The company is not currently marketing the technology for MSW conversion, although the technology could be utilized with MSW as it is similar in nature to hospital wastes.

EWI has installed one unit for the disposal of medical waste in Liverpool, U.K. This unit is currently undergoing licensing and environmental approval. A company press release indicates it has an agreement with a private firm in the U.K. to design and build its first facility to pyrolyze waste tires with the microwave heating process. It would be capable of converting 3,000 tires per day. EWI also indicates that it has received deposits for two additional orders for medical waste units. EWI also operated a 300-tire-per-day pilot plant between 1994 and 1998.

According to a material and energy flow diagram on the company website, a tire conversion facility that consumes 6,000 tires per day can provide sufficient energy to drive a 5 MWe steam turbine (if all pyrolysis oils and gases are burned in a boiler). The magnetrons and balance of plant will consume 3 MW of electrical power leaving 2 MW available for export.

Weidleplan & LIG [57]

This technology is a pyrolysis technology developed for processing waste tires. The process was originally developed by a small German engineering company, was subsequently acquired by Weidleplan

Industry GmbH, and then acquired by a company called LIG. It is our understanding that LIG was having some financial problems, but the current status of the technology is not fully known.

The process was designed for tires and includes stages for size reduction and separation, pyrolysis, combustion, and carbon activation. The pyrolysis process takes place at a temperature of 1110–1290^{o} F with the remaining syngas and pyrolysis oil converted in a two-stage combustion reactor. This process was initially tested in a small pilot scale project. A 25,000 TPY tire-shredding plant was reportedly installed in Miltzow with operation expected for the third quarter of 2002. The status of this plant is unknown.

Small Pilot Plant/ Benchscale/ Research Companies

The companies in this category have either developed small sub commercial pilot or bench scale units, or have developed the theoretical basis for a pyrolysis process that has not been demonstrated on a larger scale.

ACM Polyflow Inc. [58] [Akron, OH]

ACM Polyflow, Inc., has developed a pyrolysis plant that can be used for a variety of feedstocks. The primary goal of the process is for the development of useable petroleum-like compounds such as BTEX chemicals (primarily aromatic hydrocarbons and cycloalphatic compounds) and petroleum coke. According to the material provided, ACM Polyflow flow has conducted some tests on a batch reactor capable of processing 1,000 lbs of material over a period of approximately six hours. The process is reportedly aimed at a broad range of polymer wastes including MSW, tires, ASR, electronic waste, carpet, postconsumer and post-commercial polymeric waste, and limited amounts of PVC.

The process is currently being patented, so only limited information is available on system design. The waste undergoes primary shredding into 6" to 8" chunks and drying prior to processing. The waste enters the reactor via an airlock system. After the pyroylsis processing, the coke remains are recovered through an airlock at the bottom of the reactor and the non-condensable gases are combusted to provide thermal energy for continuous process operation.

Traidec DTV Process [59] [Sainte Foy L’Argentiere, France]

Traidec developed a pyrolysis process initially designed for the disposal of medical waste generated by a local pharmaceutical company. The reactor has a rectangular box design and uses a two-level conveyor to transport the waste. The company also developed a plant designed to target industrial waste streams and tires. A 1,320-lb-per-hour plant was constructed to process shredded scrap tires and has been extensively tested at the Traidec facility. The system was operated for extended periods of time on various waste streams. A 2-TPH plant was also engineered. The current status of the company is unknown.

Hebco International [60,61] [Montreal, Quebec, Canada]

Hebco International Inc. is a Canadian firm that is marketing a pyrolysis process for use with ASR and tires. Its pyrolysis process is based on a design the company obtained in 1995 and is currently updating. The pyrolysis process is said to utilize shredded feedstock and produces the standard bio-oil, char, and pyrolysis gases. The pyrolysis gases are combusted and with the thermal energy used in part to drive the pyrolysis process.

EEC JOULE Program [62]

A number of smaller scale fast pyrolysis programs have been funded under the EC JOULE program. Some of the fast pyrolysis processes that were a part of the EC JOULE program include Bio-Alternative (Switzerland), Egemin (Belgium), Union Fornosa (Spain), University of Aston (UK), and the University of Twente (Netherlands).

Pyrolysis technologies no longer actively promoted or for which plants have been abandoned

Ande Scientific [63,64] [Smethwick, West Mildands, UK]

Ande Scientific developed a pyrolysis process in collaboration with Wellman Furnaces Ltd. that they call the "continuous tire pyrolysis system." Ande Scientific is not currently actively promoting this process, but would be amenable to further develop the process given the appropriate financial resources. This system is designed for a capacity of 100 tires per hour, but no active facilities with the technology have been built.

The system utilizes an indirectly heated pyrolysis reactor with a magnetic separator to remove the residual steel from the tire. The pyrolysis gases produced are condensed to form a bio-oil. The remaining pyrolysis gases are combusted to provide thermal energy for the pyrolysis unit or elsewhere. Ande Scientific remains involved in processes for the disposal of tires, including a technology where the waste tires are rolled into discs and a thermoplastic elastomer made from crumbed tires.

Beven Recycling[65,66,67] [Gloucestershire, U.K.]

Beven Recycling, in conjunction with the UK Atomic Energy Authority, developed a low-volume pyrolysis process for the recovery of products from used tires. A small-scale facility based on this technology was constructed in Witney, U.K., with a capacity of approximately 10 tons of tires per week or up to 500,000 tires per year. This facility is no longer operating, but the process is described here. The tires are placed in an indirectly heated retort pyrolysis chamber in 1-ton increments (150–175 tires).

The resulting pyrolysis gases pass through a water-cooled condenser where they are condensed into a bio-oil. Any remaining gases pass through a small scrubber and then to a gas burner that produces energy to self-sustain the process. When the process is completed, the residual carbonaceous char and steel are removed from the retort after cooling and are separated. On a mass basis per ton of tires, the process produces approximately 285–350 lbs of steel, 880–905 lbs of carbon char, 505–605 lbs of bio-oil, and 420–465 lbs of synthesis gas. The process has reportedly been well tested and was considered to be proven at the current scale by a third party, Tebodin Ltd. (UK) for the Department of Trade & Industry.

Pyrovac [68] [Saint Foy, Quebec, Canada]

Pyrovac developed a pyrolytic process based on a technology developed by Dr. Christian Roy of the Universite Laval in Quebec. The reactor utilizes a conveyor system to bring wastes over horizontal plates heated to 930^{o}F in 0.15 atmosphere. Pyrovac had a commercial scale demonstration plant located in Quebec that had operated for approximately 225 hours as of April 2000. The plant has subsequently been closed for financial reasons.

Appendix E
Descriptions of Combined Pyrolysis and Gasification Processes

Table E-1 lists companies/technologies that are currently involved in combined pyrolysis/gasification technologies or in design, construction, or distribution.

Table E-1. Commercial, Demonstrated, and Actively Promoted Pyrolysis + Gasification Technologies

Company	# of Facilities	Scale (TPD)	Principal Facilities	Fuel(s)
Municipal Solid Waste				
Commercial (plants built and running)				
PKA	2	10-220	Germany	MSW, mixed wastes
Thermoselect	4	140-792	Europe, USA, Far East, South America	MSW, industrial waste
Semi-commercial				
Compact Power	1	24	United Kingdon	MSW
Demonstrator				
Brightstar Environmental*	1	170	Australia	MSW
ECN	1 planned	NA	Netherlands	ASR,MSW,sewage sludge
Tires				
Alycon	1 reference	150	Taiwan	Tires
Not Active				
Durtek				

Commercial

Thermoselect (Locarno, Switzerland) [69,70,71,72,73] [survey was provided for technology]

The Thermoselect High Temperature Recycling (HTR) was developed beginning in 1989 stemming from work in the earlier 1980s. The process uses slow pyrolysis followed by fixed-bed oxygen-blown (atmospheric pressure) gasification and ash melting. Some information indicates natural gas is burned along with a portion of the producer gas to the gasifier for supplemental energy for gasification. This may be due to variability of feedstock character (i.e., moisture, energetic value).

One of the features of the process is that minimal or zero feedstock preparation/processing is required. The process accepts unsorted MSW. Waste is loaded into a chamber where it is compacted by hydraulic press to one-fifth its original volume and moved (in plug flow fashion) through a cylindrical heating channel where drying and pyrolysis occurs. The lower end is about 570^{o} F; the waste then enters a high-temperature reactor at about 1500^{o} F. At the end of this horizontal heating/pyrolysis tubular reactor, the solid material falls into a high-temperature oxygen-blown gasifier. The gaseous and solid pyrolysis products are subsequently gasified at 2200^{o} F at the top of the gasifier and vitrified at 3600^{o} F at the bottom of the gasifier.

The synthesis gas exits the gasification reactor at 2200^{o} F and shock-cooled to below 158^{o} F in less than one-third of a second using a water quench. The synthesis gas is cleaned using a combination of acid/alkaline scrubbing and activated carbon, and further cooled to reduce moisture. A sample of the synthesis gas composition is included in Chapter 4.

* Development at this facility is apparently no longer being funded, although the facility has not closed.

The product synthesis gas can be used for energy production or possible chemicals or liquid fuels, although it appears the facilities currently operating facilities are primarily based on electricity production. The related emissions from the Karlsruhe, Germany, facility are provided in Chapter 5. Malkow (2004) indicates that electrical efficiencies of between 11% - 40% may be achieved depending on the power generation cycle used.[69] At one of the plants at Fontodoce, Italy, 200–500 KWh/t of waste was produced based on an input waste with a calorific value of 12 MJ/kg. The Juniper Report also indicates that natural gas at the rate of 51 lbs per ton MSW is supplied as an input feed with the MSW. This represents about 12% of the energy contained in 1 metric ton of MSW.

The inorganic residue from the process is maintained at a temperature of 2900°F to 3600°F to maintain the residues in a molten state. The molten material is quenched, and ferrous and non-ferrous materials are then separated magnetically for recycling. At the Karlsruhe facility, some additional effort is used to recover additional materials such as heavy metals from the materials extracted from the gas cleaning processes.

The Thermoselect technology appears to be one of the more widely applied technologies on a commercial basis. The initial development of this system was focused in Europe. A semi-commercial 110 TPD facility was built in Fondotoce, Italy, was in continuous commercial operation from 1994 to 1999.

A facility was then built in Karlsruhe, Germany, in 1999. This facility had problems that led to considerable delays in commissioning. This included the use of an emergency flare resulting in exceedences of cumulative emissions limits until a closed chamber combustion system with exhaust cleaning was installed. The 792 TPD facility was finally commissioned in 2001 and appears to have operated since then.

Recent information indicates that the facility is still having financial problems,[74] although representatives from the North American subsidiary of Thermoselect indicate that these issues are being addressed. The delays in the commissioning of Karlsruhe, in combination with other issues, resulted in problems with some other early Thermoselect orders including those at Hanau, Tessin, and Ansbach. Reportedly, the Ansbach facility has been built, but has not completed final commissioning. Thermoselect also has a number of other facilities in various stages of development in Europe, including one in Poland, two in Spain, two in Italy, and three in Ireland.

Facilities in Japan seem to have proceeded through commissioning more easily, indicating that the technology itself appears to be viable. A facility in Chiba, Japan has been operating since 1999 and been operating commercially at a capacity of 330 TPD since 2002. This plant was built by the Kawasaki Steel Corporation, Thermoselect's original Japanese partner. A second plant with a capacity of 140 TPD has been operating in Mutsu, Japan, since 2003. Additionally, plants in Mizushima KCS and Kawagoe City, Japan, are currently under construction. Other plants in Isahaya, Sainokuni City, and Yoshino, Japan, are in various stages of planning/construction. JFE is the company currently providing the Thermoselect technology for Japan.

A U.S. company, Interstate Waste Technologies, is marketing the Thermoselect process in North America and the Caribbean. Interstate Waste Technologies indicated that projects are currently being negotiated in Costa Rica, U.S. Virgin Islands, and Puerto Rico.

PKA Umwelttecnik (Aalen, Germany) [75,76,77,78]

This is a pyrolysis process followed by gas converter (cracker). MSW feedstock is preprocessed to remove glass, metals, and other marketable recyclables. The remaining material then goes through a size reduction process. Drying to below 15% moisture is recommended, but not mandatory. Other feedstocks that can be utilized with the system include automobile shredder residue (ASR), tires, industrial and plastic waste and contaminated soil.

The preprocessed material is conveyed into a rotary pyrolysis drum that is externally heated to 930–1020^{o} F by hot combustion gas (from burning natural gas during start-up, or from burning a portion of the pyrolytic gas that can be recycled if available in sufficient quantity and quality). The feedstock material takes up to one hour to progress through the drum. The pyrolytic product gases and vapors are then transferred to a gasification chamber where they are cracked to a producer gas at temperatures of 1830^{o} F, cooled, and cleaned according to the requirements for final use.

The pyrolytic char can be conditioned by grinding and separating out the ferrous and non-ferrous metals. Using a separate smelting reactor, the char fines can be gasified with added oxygen at a temperature between 2550–2730^{o} F to yield additional syngas for combustion and production of a vitrified slag. Data on the synthesis gas composition and energy output for this process are provided in Chapter 4, while data on the emissions and metals in the ash residue are provided in Chapter 5.

A PKA facility in Aalen, Germany, has been operating on a blend of MSW, commercial waste, and sewage sludge since 2001. This unit has a capacity of 28,000 TPY. The facility includes a char/ash melter. PKA has a 31,000 TPY unit installed in Freiberg/Saxony, Germany, where high aluminium content industrial waste is pyrolyzed for recovery of the aluminium. The aluminum is sent to an adjacent melting plant. Pyrolysis gas is used to supply heat for the melting plant. This facility has been operating continuously since the summer of 2001. A 9,000 TPY sewage drying plant has been operating since 1993 in Bopfingen, Germany. A smaller 0.4 TPH facility has also been used for testing since 1994.

The PKA process technology is also licensed to Toshiba Corp. of Japan and is marketed under the name Product en Energie Centrale (PEC) in the Netherlands. PEC reportedly has received approval for a 150,000 TPY facility in Defile, Netherlands, that will have three lines each of 4 TPH capacity. ECN has also operated a similar 25 kW pilot plant since 1997 for testing of various biomass wastes.

Semi-Commercial

Compact Power process [79,80,81,82,83,84]

The process by Compact Power Ltd. of the U.K. uses pyrolysis, gasification, and high temperature combustion for the processing of different kinds of waste. MSW is sorted and chipped to 3-in pieces as part of the preprocessing stage. Tires have a similar procedure applied to them, while sewage sludge must be dried to 50% moisture content.

Fed via a screw conveyor, the pyrolysis process utilizes heated tubes and converts the waste into char, ash, and producer gas. The char and the ash are gasified in a fixed-bed reactor to glean more energy from the entrained carbon. The gases from both of the chambers are combusted in a thermal oxidizer. The heat produced is used mainly for steam raising in a Heat Recovery Steam Generator (HRSG) unit, although some steam is used to gasify the discharged char. From here, the gases are cleaned with dry scrubbers and a SCR de-NO_x unit and then vented to the outside air. Recent emissions data for the commercial facility described below are included in Chapter 5.

Compact Power began operation in 1992 and built a pilot scale plant in 1994. Between 1995 and 1999 a series of trials were conducted at the Compact Power Plant to obtain emissions and performance data. The company began preparations for a commercial facility in 1998 at a waste transfer station at Avonmouth in Bristol, U.K., in 1998.

Construction began in early 2000 and was completed by April 2001, and the facility received a permit to operate in September 2001. The plant began continuous operation in January 2002. The facility operates two lines with a capacity of 1,100 lb per hour each or an annual capacity of 9,000 TPY. Recent news releases indicate the company is looking to sell, but still operate, the facility to provide capital for additional ventures and expenses. News releases also indicate that Compact is working with science and technology group QinetiQ to develop a waste process plant for use on ships and with Spanish company Cadagua, a subsidiary of engineering group Ferrovial, for the rights to use the primary technology in Spain.

Demonstration

Brightstar Environmental—SWERF (Solid Waste and Energy Recycling Facility) Process [85,86,87,88 89] (Queensland, Australia) [This company responded to the survey and provided literature]

Energy Developments Ltd. (Australia) is the majority owner company of Brightstar Environmental. Brightstar Synfuels (Texas) is a minority holder.

The SWERF process accepts unsorted MSW. The material is first treated in an autoclave (steam and pressure) to create a manageable pulp and reduce odors and pathogens, after which standard material handling/separation equipment removes metals and rigid plastics for recycling or disposal. The remaining pulp is washed to remove sand and glass followed by pulp drying and storage. Energy for drying is provided by exhaust heat. The gasifier system works at optimum efficiency when the material is shredded to a <2 in size and has a moisture content below 10%.

The core conversion technology consists of two steps, pyrolysis followed by char steam gasification. The producer gas is run through reciprocating internal combustion engines for process heat and power for export.

There is a commercial scale (55,000 TPY capacity) demonstration in Wollongong, N.S.W., Australia, that has been undergoing commissioning since early 2001. There were problems with the char gasification component of the process which caused the parent company Energy Developments Ltd. to cease funding further development and search for a buyer of its portion of the Brightstar Environmental stock (~88%). The Wollongong City Council announced that the SWERF facility has ceased operation in March, 2004 because EDL could not find an international partner to help share the risk. The facility will be used as a MRF and transfer station. It is not known whether SWERF technology proposals in the UK and the USA are proceeding.

Energy Research Center of the Netherlands (ECN) [90] (Amsterdam, Netherlands) [This company responded to the survey and provided literature]

ECN is involved in a variety of areas related to the development and implementation of conversion systems for biomass and waste. This work includes both experimentation as well as review/analysis studies and is done in collaboration with industrial partners. The company is working on a two-stage process using a combination of low-temperature pyrolysis (1020^{o}F) and high-temperature gasification (2250^{o}F). The resultant producer gas can be used for combined heat and power or chemical synthesis. A solid residual of charcoal, metals, and minerals is produced, which is converted in a smelter into synthetic basalt (clean construction material), a metal mixture (ore replacement) and CO-rich gas. The technology can be used with a range of feedstocks including, but not limited to, MSW, ASR, electronic scrap, sewage sludge construction and demolition waste, contaminated sludge, and chemical waste. ECN currently plans to implement a demonstration plant in Groningen, Netherlands.

Currently focusing on electronic wastes, ECN gasification technology is primarily used in the recycling of bromine and the energy content of the plastics used in circuitry. Three-quarters of the energy from the plastics is captured in the synthesis gas and the char, with the synthesis gas fraction retaining the majority of the energy (approximately 53%) and the char retaining approximately 22%. The total process energy efficiency will range from 30 to 35% (LHV) and perhaps as much as 50% when combined with fuel cell technology.

Tires

Alcyon Engineering SA[91,92] (Switzerland) [This company provided literature concerning it's process.]

Alcyon is a Swiss engineering company that has developed a pyrolysis process known as TiRec. The company has a separate TiRec FUEL process that incorporates only the pyrolysis unit and a TiRec COGEN process that incorporates the pyrolysis reactor and a separate generator/gasification process for the pyrolysis products. The TiRec COGEN process utilizes a separate gasification system for the semi-coke by-product and a generator for the gases and oils produced in the pyrolysis process. The pyrolysis reactor operates at a shell temperature of 1022^{o} F, resulting in a product temperature of approximately 790^{o} F, and a pressure of approximately 0.8 atmosphere. The reactor operates in a batch mode and is capable of handling up to three batches of 1,100 lb each per hour.

Alcyon is currently operating a TiRec plant in Kaohsiung, Taiwan. The plant includes two lines capable of processing 24,802 metric TPY each with a typical operating time of 7,500 hours per year. Each line incorporates two separate pyrolysis reactors. The plant is operated by a customer and not directly by Alcyon, so only limited feedback on the plant operation was available.

Appendix F
Descriptions of Gasification Processes

Table F-1 displays the companies that have, to date, shown an interest in either promoting, designing, or constructing gasification facilities. In this table, companies with multiple commercial units in place, or single commercial units with orders for addition units, are considered to be fully commercial. Companies with single facilities in commercial operation are considered semi-commercial. Companies with pilot plants on a scale of at least 10 TPD are considered precommercial.

Table F-1. Commercial, Demonstrated, and Actively Promoted Gasification Technologies

Company	Number of Facilities	Scale (TPD)	Principal Facilities	Fuel(s)
Large Scale (Commercial)				
Alstom	50+	24-220	Japan	ASR, Tires, wood and agricultural wastes, sludge
Babcock & Wilcox Volund	2	N/A	Denmark	Wood
Chemrec	2	300-550	NC, Sweden	Black liquor
Energy Products of Idaho	1	600	OR	Biological and industrial waste
Enerkem	3	250	Canada	Biomass, pulp & paper
Ferco	1	250	VT	Wood
Global Energy	3	N/A	LA, IN, Germany	Coal, non-hazardous industrial waste
Krupp Uhde Prenflo	2	150	Germany, Spain	Coal, MSW, ASR, EEESR
Nippon	1	400	Japan	MSW, plastic waste
Noell (Babcock Borsig)	1	120	UK, Germany	MSW, industrial waste, oil, coal
Primenergy	4	100 - 500	AR, Italy, MS	Rice hulls, olive oil
PRM	13	15-820	AR, OK, MS, Malaysia, Costa Rica, Australia	Rice husk, agri-waste, dried sewage sludge
Shell	2	220	Netherlands	Refinery residues
Medium Scale (Commercial)				
Babcock Borsig Power	2	~45	Austria	Wood and agricultural wastes
Foster Wheeler	6	N/A	Finland, Sweden, Portugal	RDF, wood, packaging material
Heuristic Engineering	8	N/A	USA, Canada	Wood
Minergy	3	1200 (1)	Wisconsin, Ill.	Sludge/sediment/soil
MTCI Thermochem	2	25-50	USA	RDF, paper mill sludge
Nathaniel	1	N/A	USA	Industrial wastes
Organic Power	3	8-50	Norway	MSW, biomass, industrial waste
Sacone Brookes	3	0.5-25	UK	Clinical and hospital waste, animal waste
Sumitomo	1	20	Japan	MSW, ASR, ESR
TPS	2	N/A	Brazil, UK, Sweden	RDF, agricultural and bio waste
Waterwide	1	310	Australia	Wood and biomass

Company	Number of Facilities	Scale (TPD)	Principal Facilities	Fuel(s)
Pilot Scale / Demonstration				
B9 Energy	1	5	Northern Ireland	Wood
BG Technologies	+400	N/A	India	Agricultural wastes
Community Power Corp.	6	N/A	US, Phillipines	Wood
CPL Biomass	1	20	UK	Sewage sludge
Emery Energy Company, LLC	2	<600	UT	Biomass, scrap tires, coal
FERCO Enterprises, Inc.	1	10 - 300	VT	Agricultural wastes, RDF, Wood
Host	2	N/A	Netherlands	Wood, chicken litter, sewage sludge
Improved Converters Inc.	1	N/A	Sacramento, CA	MSW, tires
Intellergy	1	N/A	Hayward, CA	MSW, pharmaceutical waste, agricultural waste
KARA Energy Systems	1	N/A	Netherlands	Biomass
Krupp Polysius	2	14-72	Germany, Switzerland	Tires, wood
MFU	1	30-150	Germany	Wood waste, industrial waste
NKK	1	24	Japan	ASR, MSW, MPW
Renewable Resources Alliance, LLC	0	<600	Santa Barbara, CA	Green waste, food waste
RGR Ambiente	1	10	Italy	RDF, tires, carpet waste
Texaco	1	120	Netherlands	Mixed plastic wastes
Thermogenics	1	600	KS	Wood, biomass, RDF
UET		N/A	Germany	Sewage sludge, bio wastes
Waste Gas Technology	1	<1	UK	Sewage sludge, biomass
Waste to Energy	1	8	UK	Sewage sludge
Wellman	1	N/A	UK	Wood
Research / Bench-scale				
JND	1	N/A	UK	MSW
McMullen	1	N/A	PA	RDF
PKA (Coras-H)	1	35	Germany	Sewage sludge
UCR CE-CERT Viresco Energy, LLC	1	N/A	Riverside, CA	Sewage sludge, wood chips, rubber, plastics

The companies under this category have all developed processes that are either being currently used for MSW as a primary feedstock or are designed to do so.

Nippon Steel (Tokyo, Japan)

Waste Melting Process

The Nippon Steel "Waste Melting Process" evolved from metallurgical processing technology. Facilities using this process accept unsorted MSW that has been processed to required particle size. The Nippon Steel process uses a fixed bed gasifier (not clear if pressurized), with enriched oxygen air injection in the melting section. Coke is added to the MSW (100 lb per ton MSW or 5% by weight) input feed. The coke reacts with the oxygen and pyrolytic gases at the air injection and melting region (Heermann, C., et al (2001) [93].

Coke is apparently added to help provide energy for full ash melting. Limestone is also added (~5% by weight of input) to provide some pH buffering of the melt. The producer gas is burned in conventional steam boilers from which heat and power can be generated. Output materials include granulated slag (180 lb-per-ton input), recyclable iron (20-lb-per-ton input) and fly ash (60-lb-per-ton input) that is sent to landfill. Mercury and heavy metals present in the waste are found in the fly ash and producer gas, requiring that these streams be managed appropriately before discharge.

Approximately a dozen plants (operational or being commissioned) in Japan are using this process. The capacities range from 110 to 500 TPD.

In Table F-2, Nippon Steel's existing and planned facilities are displayed, along with the planned energy use, the wastes being processed, and the capacity. All facilities have using this process been constructed in Japan to date.

Table F-2. Nippon Steel Facilities

No.	Client	Waste Types	Capacity (TPD)	Start-up	Waste Heat Utilization
1	Kamaishi City, Iwate Pref.	MSW; CFC gas	110 / 2 sets of 55	Sep. 1979	Hot water recovery
2	Ibaraki City, Osaka Pref.	MSW; CFC gas	500 / 3 sets of 167	Aug. 1980	Waste heat boiler / power generation (capacity: 10,000kW)
3			332 / 2 sets of 166	Apr. 1996	
4			166 / refurbished	Apr. 1999	
5	Iryu Health Facilities Administration Union, Hyogo Pref.	MSW	132 / 2 sets of 66	Apr. 1997	Waste heat boiler / power generation (capacity: 1100kW)
6	East Incineration Facilities Union, Kagawa Pref.	MSW; incineration residues	144 / 2 sets of 72	Apr. 1997	Waste heat boiler / power generation (capacity: 1600kW+1100kW)
7			72 / annexed	Apr. 2002	
8	Lizuka City, Fukuoka Pref.	MSW; sludge	198 / 2 sets of 99	Apr. 1998	Waste heat boiler / power generation (capacity: 1200kW)
9	Itoshima Regional Fighting & Facilities Union, Fukuoka Pref.	MSW; sludge; sludge-incineration residues; CFC gas	220 / 2 sets of 110	Apr. 2000	Waste heat boiler / power generation (capacity: 3000kW)
10	Kameyama City, Mie Pref.	MSW; landfill wastes	88 / 2 sets of 44	Apr. 2000	Waste heat boiler / power generation (capacity: 1250kW)
11	Akita City, Akita Pref.	MSW; sludge; incineration residues	440 / 2 sets of 220	Apr. 2002	Waste heat boiler / power generation (capacity: 8500kW)
12	Maki Town, 3 other Towns & Villages Sanitary Union, Niigata Pref.	MSW; sludge; landfill waste; CFC gas	132 / 2 sets of 66	Apr. 2002	Waste heat boiler / power generation (capacity: 1500kW)
13	Kazusa Clean System Co., Ltd. [Phase-1] Chiba Pref.	MSW; sludge; incineration residues	220 / 2 sets of 110	Apr. 2002	Waste heat boiler / power generation (capacity: 2300kW)
14	Takizawa Village, Iwate Pref.	MSW	110 / 2 sets of 55	Oct. 2002	Waste heat boiler / power generation (capacity: 1200kW)
15	Narashino City, Chiba Pref.	MSW; sludge	222 / 3 sets of 74	Nov. 2002	Waste heat boiler / power generation (capacity: 2400kW)
16	Kochi West Environmental Facilities Union, Kochi Pref.	MSW; sludge	154 / 2 sets of 77	Dec. 2002	Waste heat boiler / power generation (capacity: 1800kW)

No.	Client	Waste Types	Capacity (TPD)	Start-up	Waste Heat Utilization
17	Tajimi City, Gifu Pref.	MSW; sludge	188 / 2 sets of 94	Apr. 2003	Waste heat boiler / power generation (capacity: 1990kW)
18	Toyokama Hoi Sanitary Union, Aichi Pref.	MSW; incineration residues; sludge; Sludge-incineration residues	144 / 2 sets of 72	Apr. 2003	Waste heat boiler / power generation (capacity: 1850kW)
19	Oita City, Oita Pref.	MSW; sludge	429 / 3 sets of 143	Apr. 2003	Waste heat boiler / power generation (capacity: 9500kW)
20	Genkai Environmental Union [Munakata Plant], Fukuoka Pref.	MSW; sludge	176 / 2 sets of 88	Jun. 2003	Waste heat boiler / power generation (capacity: 2400kW)
21	Seino Waste Management Union, Gifu Pref.	MSW	99	Apr. 2004	Hot water recovery
22	Kita-kyushu Eco Energy Co., Ltd. Fukuoka Pref.	Industrial waste (w/ ASR)	354 / 2 sets of 177	Feb. 2005	Waste heat boiler / power generation (capacity: 13,600kW)
23	Shimada City & Kita-Haibara Regional Sanitary & Fire Fighting Union, Shizuoka Pref.	MSW; sludge	162 / 2 sets of 81	Mar. 2006	Waste heat boiler / power generation (capacity: 1990kW)
24	Kita-kyushu City [Shin-Moji Plant], Fukuoka Pref.	MSW; sludge	795 / 3 sets of 265	Mar. 2007	Waste heat boiler / power generation (capacity: about 22,000kW)
25	Kazusa Clean System Co., Ltd. [Phase-2] Chiba Pref.	MSW; sludge	276 / 2 sets of 138	Apr. 2006	Waste heat boiler / power generation (capacity: 5000kW)
26	Yangsan City, Gyeongsang Nam-Do, Republic of Korea	MSW	220 / 2 sets of 110	Oct. 2006	Hot water recovery

Alstom/Ebara (France, Switzerland and Japan) [This company responded to the survey and provided literature.]

"TwinRec" and "UEP" processes.

Alstom Power (Meudon-la-Foret, France) acquired ABB Enertech in 1999. ABB had exclusive license of Ebara's (Japan) fluidized bed technology, which has several commercial facilities in Japan.[94] Ebara builds and operates full MSW combustion facilities in Japan and some other Asian countries. Ebara also has developed the TwinRec and EUP gasification processes through the Japanese initiative to develop more sustainable waste disposal technologies.

TwinRec Process

Ebara has long experience with fluidized bed combustion systems for waste materials. It adapted its bubbling fluidized bed reactor to operate as a gasifier and coupled it with a secondary combustion chamber, where the producer gas is burned with the addition of secondary air. This is an atmospheric pressure air-blown process. The larger ash particles, along with metal and glass pieces, leave the gasifier bed as bottom ash from which the metals can be separated. Smaller ash and char particles are carried over with the producer gas and enter the combustion chamber that operates at high enough temperature to melt the inorganic material carried over.

The slag is water-quenched, which yields vitrified granules. It is possible to grind the bottom ash from the gasifier portion and inject it into the melting combustor (at higher processing and energy expense) to slag essentially all of the inorganic material present in the original feedstock. This ash melting process creates a vitrified residue which has low leachability characteristics. Table F-3 shows existing facilities using the TwinRec process.

Table F-3 Ebara TwinRec Gasification Facilities[95]

Location	Commissioning Date	Feedstock	Mass (%)	Scale (t/y)	LHV (MJ/kg)	Thermal Capacity (MW)	Output Elect. (MWe)
Kurobe	Dec, 2000	Automotive Shredder Waste Waste Plastics copper slag + sorbents	41 13 46	22,000	10.2	7.4	
Minami-Shinshu	Mar, 2003	MSW	100	34,000	8.4	2x4.5	
Joetsu City	Mar, 2000	Dry Sludge Waste Plastic	68 32	57,000	12.3	2.2	
Chuno Union	Mar, 2003	MSW	100	61,000	11.3	3x7.3	
Sakata Area	Mar, 2002	MSW	100	72,000	10.9	2x12.3	2
Ube City	Nov, 2002	MSW	100	72,000	12.5	3x9.5	
Nagareyama City	Feb, 2004	MSW	100	75,000	11.7	3x9.3	
Kawaguchi	Nov, 2002	MSW	100	153,000	13	3x21.0	12
Aomori	Feb, 2000	Automotive Shredder Waste Sewage Sludge	70 30	160,000	14.3	2x40	17
Kuala Lumpur Malaysia	May, 2006	MSW	100	548,000	9.6	5x33.3	

The following is excerpted from Ebara website engineering abstracts (Review No.197, 2002)[96]

Japan's first municipal waste fluidized-bed gasification-melting furnace system, equipped with a power recovery steam turbine, has started operation at Sakata City, Japan. The dioxin concentration in the exhaust gas of this system meets the local standard. The produced slag meets leachability requirements and is used as pavement material (inter-locking blocks). The exhaust gas from the furnace is used in a heat recovery boiler to produce steam for a steam turbine (max. output 1990 kW)Excess electricity produced is being sold to the local electricity company (though net power to the grid is not known).

UEP Process

Ebara and Ube Industries Ltd. (a plastics and chemical company) developed this process for recycling the chemicals in waste plastic. Based on the TwinRec process, the UEP system uses two pressurized gasifiers in series. The process operates up to 10 atmospheres and is oxygen-blown. The first gasifier is essentially the same bubbling fluidized bed as used in TwinRec and runs at a relatively low temperature. The produced gas flows to the second reactor where additional oxygen is injected. The temperature in the second reactor is much higher and inert material melts (or slags). The slag and gas passes through a water trap after the second reactor where the slag solidifies. The remaining gas can be used for energy production, liquid fuels production, or chemical feedstocks. Table F-4 shows existing facilities using the UEP process.

Alstom reportedly[97] markets the Ebara reactor modified to operate as a gasifier targeted for higher energy containing fuels (automobile shredder residue, plastics, electronic scrap, and tires). This process can also handle other domestic and urban residues. But an Ebara (Environmental Engineering Group) office in Zurich, Switzerland claims to represent the Ebara TwinRec and UEP processes in Europe.

No Alstom/Ebara European installations were identified, but several of the Ebara TwinRec and UEP facilities are operating in Japan (See Tables F-2 and F-3).

Table F-4 Ebara UEP Pressurized Gasification for Chemical Recycling Facilities[98]

Location	Commissioning Date	Feedstock	Scale (t/y)	Product
Ube City	1999	Waste Plastic	11,000	Fuel gas or feedstock for ammonia production
Ube City	2002	Waste Plastic	24,000	Feedstock for ammonia production
Kawasaki	Expected 2003	Waste Plastic	107,000	Feedstock for ammonia production

Other Japanese Technologies [Hitachi-Zosen, NNK, Sumitomo (Krupp Precon)]

Japan has in some respects led the way in producing gasification conversion technologies for wastes of all types, MSW included. Here is a short list of companies in Japan that are currently developing and constructing gasification facilities, mostly exclusively in Japan.

Hitachi-Zosen

Hitachi-Zosen has two fluidized bed systems: a typical BFB incinerator and a horizontal and internal circulating bed (HICB). The pyrolysis gases from the HICB are fed into rotating furnace, which melts the incombustibles into slag.

Table F-5 displays the planned and the current facilities running on Hitachi-Zosen gasifiers.

Table F-5. Hitachi-Zosen Systems Planned and Operating

No.	Location (all Japanese)	Capacity (TPD)	Start-up
1	Gifu	33	1998
2	Nara	150 / 2 sets of 75	2001
3	Ishikawa	160 / 2 sets of 80	2003
4	Kagawa	300 / 3 sets of 100	Mar-04
5	Nagasaki	58 / 2 sets of 29	2003

NKK Waste Melting Process

NKK, a large Japanese engineering firm, has developed a waste melting technology that uses gasification. The waste is gasified at temperatures in excess of 1800^o F and, in the same step, melted in a Nippon Steel shaft furnace. The molten ash and slag is separated from the synthesis gas, which is cleaned and combusted to provide electricity. NKK has one pilot plant with a capacity of 1 TPH. No further data has been provided from the corporation.

Sumitomo N3T (a.k.a. Krupp PreCon)

Sumitomo has developed technology first designed by Krupp-Uhde. This technology was formerly known as PreCon. Sumitomo now calls it New Thermal Treatment Technology (N3T). Originally, the PreCon process was an amalgamation of the High Temperature Winkler (HTW) process and an ash melting process known as CEP, developed by Molten Metal Technology (MMT) Inc. Sumitomo acquired the license for certain components of the PreCon process and integrated these processes with its own ash melting technology.

The HTW gasifier is a fluidized bed gasifier operating at an elevated pressure, between 1 and 5 atmospheres, and at temperature between 1470–2010^{o}F. The ash produced from the process is removed via cyclone at the top of the FB reactor and returned to the bed. The ash from the bottom is processed in a short kiln. The resultant slag is being marketed as construction material.

Table F-6 shows the facilities that Sumitomo has planned and is currently running.

Table F-6. Sumitomo N3T Plants in Planning

No.	Location	Capacity	Start-up	Gas Utilization
1	Sikuku, Japan (Niihama Facility)	20 TPD	1999	Demonstration
2	East Japan (Kashima Steel Works, Sumitomo Metals)	Approx. 60,000 TPY	2004	Power generation; utility gas
3	West Japan (Yamaguchi Plant, Kyoei Steel)	Approx. 60,000 TPY	2004	Fuel to the reheating furnace

SVZ concept

One of the oldest and most historically important gasification facilities is the Schwarze Pumpe site in former East Germany. This site is operated by Sekundarrohstoff-Verwertungszentrum (SVZ), which is now a subsidiary of Global Energy, Inc., of the U.S. The plant began operation in the 1950s for the production of town gas from coal in the area, but was converted in and commissioned to operated on waste in 1997. The facility reported treats >450,000 TPY of solid wastes and another 55,000 TYP of liquid wastes,[99,100,101,102,103] although a recent gasifier survey has reported even higher values.[104] The feedstock types accepted are diverse and include postconsumer plastics, ASR light fractions, sewage sludge, tire-derived fuel (TDF), wood waste, RDF, oil, paint, and refinery residues. The facility produces 75 MW of electricity and 300 TPD of methanol.

The facility has 10 separate gasifiers. Seven are “Lurgi Dry Ash” gasifiers; the other three are a Lurgi multi-purpose gasifiers (MPG), British Gas-Lurgi, and Noell KRC. The system is shown schematically in Figure F-1.[105,106,107,108,109,110,111,112,113,114,115,116,117.] A schematic of the facility layout is provided in Figure F-2. The pretreated and processed waste is gasified at high pressure (25 atmospheres) using oxygen and steam at temperatures of 1472–2372º F in the seven grate-type fixed-bed dry-ash reactors. The slagging British Gas-Lurgi gasifier operates at a temperature of about of 3000º F. Dry ash gasifiers are nonslagging in that the ash material does not reach its melting temperature.

The British Gas-Lurgi gasifier was developed as part of a cooperative development effort by British Gas, plc. and Lurgi Oel Gas Chemie GmbH.[118,119,120.] The semi-solid and liquid wastes are gasified using two 15-ton-per-hour slagging multi-purpose reactors at temperatures of 2912–3272º F.[121,122] This multipurpose reactor is an entrained flow reactor that was invented by SVZ and modified by Lurgi to allow operation in slagging, ash quenching, or boiler mode. The gas produced by the reactors is water-quenched and used to produce steam for gasification and subsequently subjected to effective CGC. SVZ quotes an efficiency of >45%.It should be noted that a British Gas-Lurgi system was also approved for an MSW co-fueled IGCC coal demonstration project that is integrated with a 1.25M molten carbonate fuel cell. This plant is through Kentucky Pioneer Energy, LLC (KPE), a subsidiary of Global Energy, Inc., and is located in Trapp, Kentucky, at the East Kentucky Power Cooperative’s Smith site.[123,124,125]

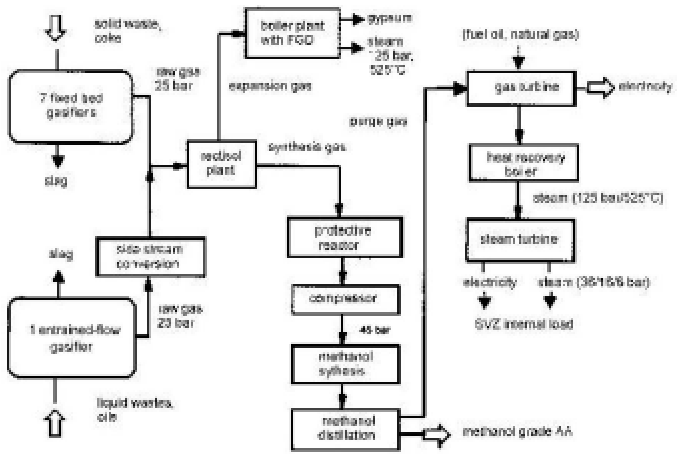


Fig. F-1. Schematic of the SVZ Waste Utilization Concept in Polygeneration Configuration.[126]

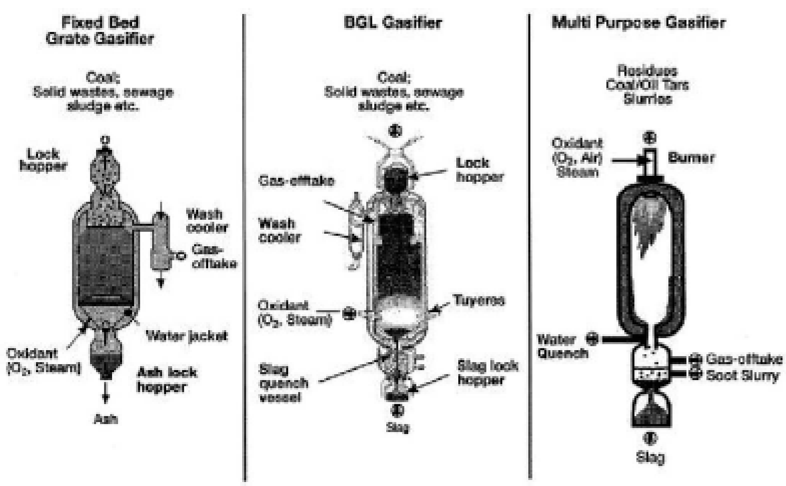


Fig. F-2. Type of Gasifiers Used at the SVZ Installation.[127]

Enerkem, Université de Sherbrooke, and KEMESTRIE INC. (Sherbrooke, Quebec, Canada)

BIOSYN process

Enerkem Technologies Inc. is a subsidiary of the Kemestrie Inc. Group, a spin-off company of the Université de Sherbrooke, founded in 1992. It is the sole owner of a technology portfolio resulting from investments begun in 1981 by the Canadian government as part of its National Energy Plan. The company continued in partnership with the Ministère des Resources Naturelles du Québec, the Centre Québécois de Valorisation de la Biomasse (CQVB), the Université de Sherbrooke and Kemestrie Inc. A principal member of the company is Dr. Esteben Chornet, a member of the staff at the National Renewable Energy Laboratory (NREL)[128] and a professor of Chemical Engineering at Université de Sherbrooke[129].

This process utilizes a bubbling fluidized bed (BFB) gasifier, with air or oxygen operating at pressures up to 16 atmospheres. The process includes proprietary catalysts for cracking tar and other components in the producer gas. The process is capable of operating on biomass, sorted MSW, and plastics. Enerkem will provide performance guarantees of minimum energy conversion efficiency (solids to conditioned synthesis gas) of 70%* as well as composition of the synthesis gas based on the composition of the feedstock

The Poligás plant in Ribesalbes (Castillón), Spain, owned by Poligás Ambiente, S.L., and built by Environmental International Engineering, S.L. (EIE) has recently gone into operation. Spain's Institute of Energy Diversification and Efficiency (IDAE) and the waste management company Revima participated in the project. Financing was provided by regional government (Valencia) and EU funds. The plant is fueled with discarded plastics wrappings from the ceramics industry. This plant reportedly[130] is generating 7 MWe (80 MMBTU/h of synthesis gas) from approximately 27,560 TPY waste plastic. It has run for approximately 5,000 hours since August 2003.

In 2002, Enerkem began working with the City of Sherbrooke to convert waste into synthetic gas (BioSyngaz-Estrie project). Federal, provincial, and corporate monies financed the project. The pilot unit was designed and constructed with the capacity to convert 2.8 tons of sorted municipal waste residue per day.

MSW Pilot Plant in Sherbrooke (BioSyngasEstrie Project)

Enerkem, the City of Sherbrooke, and provincial and federal agencies have partnered to build and operate a pilot plant based on the BIOSYN process for sorted MSW. Reportedly, the system ran at a capacity of 5 TPD for more than 1,000 hours since 2002 with technical reports and feasibility studies that should be complete at this time.

Foster Wheeler Energia Oy (Finland) [This company responded to the survey and provided literature]

Lahti, Finland

Foster Wheeler, in cooperation with Kymijärvi Power Station at Lahti, Finland, has installed an atmospheric (air-blown) circulating fluidized bed (ACFB) gasifier next to the coal/fossil fuel-fired utility boiler. The thermal capacity of the gasifier is 40–70 MWth depending on the moisture content of the fuel (which can be up to 60%). The producer gas from the gasifier is co-fired in the boiler. The ACFB is sized to provide up to 15% of the energy input to the boiler (replacing up to 30% of the coal feed). The lack of gas cleaning limits the fuels to woody biomass and low/no chlorine containing waste-derived fuels (some amount of separation of residential or municipal wastes to remove chlorinated plastics). Table F-7 describes composition of the refuse-derived fuel. The project demonstrates commercial scale feasibility of close coupled gasification of low quality "opportunity" fuels which otherwise could not be utilized in the combustion boiler.

Päijät-Hämeen Jätehuolto Oy

A municipally owned waste management company (Päijät-Hämeen Jätehuolto Oy) started the processing of refuse-derived fuel in 1997. In the first year of operation, 1998, just less than 9000 tons of residential

* Note: energy conversion efficiency for overall process (through to electrical generation) would be about 20% (steam turbine) up to about 30% (large reciprocating internal combustion).

refuse fuel was gasified, accounting for 22% of the energy through the gasifier (the bulk of the gasifier energy came from wood residues). For the year 2000, more than 22,000 tons of refuse fuel was consumed, accounting for 36.6% of the energy acquired through the gasifier.[131]

Table F-7 Composition of Refused Derived Fuel at Lahti [132]

Component	% by weight
Plastic	5–15
Paper	20–40
Cardboard	10–30
Wood	30–60

Varkaus Finland

Foster Wheeler installed a bubbling fluidized bed gasifier (BFB) as part of an integrated recycling process at the Corenso United Oy, a large paper and cardboard/packaging material manufacturer. Used multilayer packaging material (which includes plastic film and aluminum foil layers, for example, Tetrapak aseptic drink containers) is recycled by separating as much of the cellulose material from the plastic and aluminum as possible and then gasifying the remaining plastic and aluminum containing portion in the Foster Wheeler BFB. As shown in the process diagram found in note 133, apparently vaporized aluminum is recovered from the hot gas. The aluminum is solidified into ingots and reused. The energy from the gas replaces some of the fossil fuel used to raise process steam. The gasifier is 40 MWth in capacity and recovers about 3,000 ton per year of aluminum and gasifies 27,000 tpy polyethylene.

TPS Termiska Processer AB (Nyköping, Sweden)

TPS is an employee-owned company in Sweden with a fairly long history in gasification and combustion technologies for heat and power fueled by biomass and coal. Using funds provided by the Swedish National Energy Administration, the European Community (various energy agencies), and private companies, TPS is currently conducting research and development. TPS specializes in fluidized bed, both circulating (CFB) and bubbling (BFB) types operating in combustion or gasification modes. Gasifier attributes include atmospheric or pressurized, using air, oxygen, or steam injection.

The CFB designs of the company are licensed (under the name of Studsvik) to several large boiler manufactures throughout the world, including Babcock and Wilcox (USA), Kvaerner (Sweden), Austrian Energy (Austria), and SER Consortium (Brazil).

TPS licensed the CFB process to Ansaldo Aerimpianti SpA of Italy in 1989 and provided the design of two gasifiers to be fueled by pelletized refuse-derived fuel (RDF). The plant was built by Ansaldo and began operation in 1991.

The TPS technology uses a starved-air gasification process in a combined bubbling and circulating fluidized bed reactor operated at 1560^{o} F and near atmospheric pressure. The two 15MWth CFB gasifiers consume 100 TPD (each) of pelletized RDF from nearby Florence. The gasifiers are air-blown and operate slightly above atmospheric pressure near 1560^{o} F (below ash melting point).

RDF is fed to the fluidized bed. Air is used as the gasification/fluidizing agent. Part of the air is injected into the gasifier vessel through the bottom section and the remainder higher up in the vessel. This pattern of air distribution causes a density gradient in the vessel. The lower part maintains bubbling fluidization that allows coarse fuel particles adequate residence time for good gasification reactions. The secondary air introduced higher up in the vessel increases the superficial velocity of air through the reactor so that smaller, lighter particles are carried away in the gas flow.

The process gas from each gasifier passes through two stages of solids separation before being fed to a furnace/boiler. The flue gas exiting the boiler is then cleaned in a three-stage dry scrubber before being exhausted through the stack. Alternatively, some of the raw gas stream can be sent to a nearby cement factory, without cleaning, to be used as fuel in the cement kilns.

TPS Termiska has developed a patented catalytic tar-cracking system. Immediately downstream of the gasification vessel, a dolomite (mixed magnesium-calcium carbonate) containing vessel catalyzes most of the tars formed in the gasification process and breaks them down into simpler compounds with lower molecular weights and melting points. The dolomite also will absorb acids in the flue gas, including HCl and sulfur oxides. The product gas can then be cooled and passed through conventional scrubbing systems without operational problems. After cooling, the syngas can be compressed and is reportedly clean enough to be used with a combined cycle turbine. The system can feed gas to a nearby cement plant if electricity economics are unfavorable.

Greve, Italy

A recent case study of the Greve facility was published by the IEA Task 36[134](Energy from Solid Waste Management Systems). The plant has experienced operational problems due to boiler fouling from condensed tar and fly ash deposits. A two-phase remediation program was undertaken late in 1997 with planned completion in 2000. The status of the operational problems and repairs is unknown since the plant owners have not returned requests for information.

TPS is also involved in integrated gasification combined cycle (IGCC) systems fueled by biomass. A demonstration plant of this type operated briefly in the UK (ARBRE project).[135] The facility is wood-fueled with a design capacity of 8MWe. The project went bankrupt and the disposition of the facility is not known. TPS was involved in design work for two projects in Brazil for IGCC plants. One plant would be fueled by bagasse and sugar cane trash, and eucalyptus trees would fuel the other. However, apparently the projects have halted due to lack of investment funding and energy prices.

Intellergy Corp.[136,137] (Berkeley, CA)

Intellergy has developed a gasification/steam reforming system for processing MSW and other wastes. The process uses MSW or other wastes, CO_2, and water in a non-catalytic gas-phase reactor. A two-stage rotary kiln is used as the reactor, which is heated by natural gas. The reactor operates in a temperature range between about 1300º F and 2000° F to convert the MSW, CO_2, and steam into a synthesis gas composed of about 55 percent hydrogen and 35 percent carbon monoxide.

The synthesis gas can be split into two streams. One stream is sent to a gas-to-liquid catalytic reactor to convert the synthesis gas to a light oil and paraffin wax, methanol, or other products. The other stream is sent to a fuel cell manufactured by Siemens-Westinghouse or FuelCell Energy to produce electric power. Intellergy is designing and performing feasibility studies for a number of locations including Hayward, California; Toronto; Puerto Rico; the Dominican Republic; and Brisbane, Australia. They are currently in a predesign, post feasibility stage on plants capable of processing 2,000–3,000 TPD of agricultural waste for the Caribbean and Hawaii. They also have designed plants of 4–40 TPD capacity for pharmaceutical wastes, including a 4 TPD facility being planned for Hayward.

Emery Energy Company (Salt Lake City, Utah) [This company responded to the survey.]

The Emery Energy Company has developed a fixed bed gasification process that can potentially be used for a range of feedstocks, including MSW as RDF, scrap tires, and other biomass feedstocks. The system incorporates a downstream syngas cleaning process that removes gaseous pollutants prior to its combustion for power generation. Process flow diagrams for a 20 MW_e and a 70 MW_e facility are shown in Figures F-3 and F-4. The Emery technology is currently in the precommercial/pilot plant stage of development. Emery has a 25 TPD/ 7 MW_{th} pilot plant in central Utah and a new 3 MW_{th} pilot plant in Salt Lake City. Emery has also designed a 70 MWe gasification system with INEEL/Bechtel and GE Power Systems and gasifier vessels up to 600 TPD. The project is receiving US DOE funding.

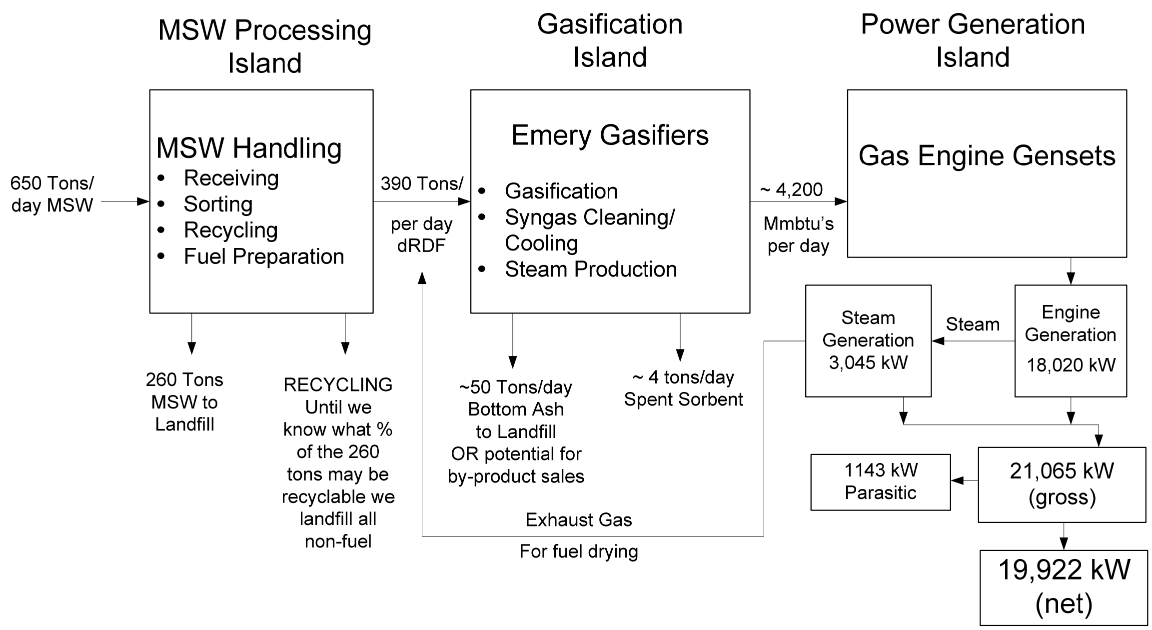


Fig. F-3. Process Flow Diagram for 20 MWe MSW Gasification Power Plant recently proposed to a municipality in California

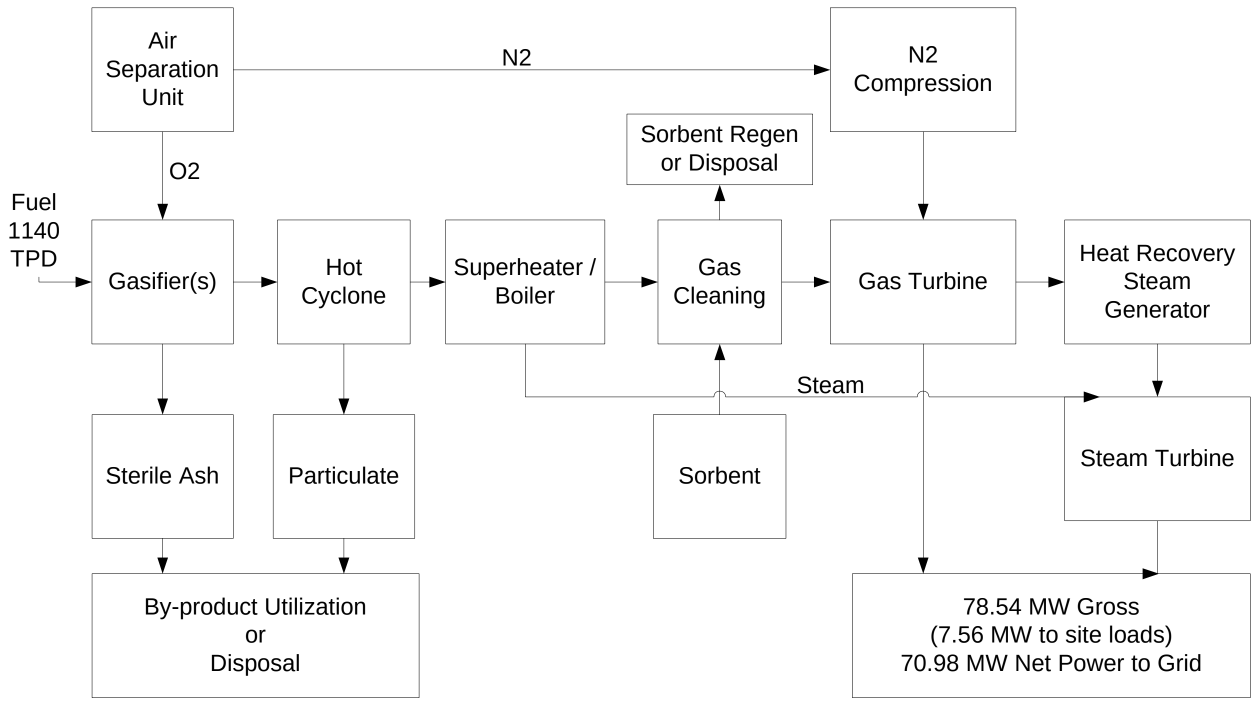


Fig.F 4. Simplified Process Flow Diagram for 70 MWe Biomass Gasification Power Plant (DESIGNED UNDER U.S. DOE Contract DE-FC26-01NT41531)

Duratek Process (Oak Ridge, Tennessee) [This company responded to the survey and provided literature]

Duratek has developed a gasification/steam reforming process that has been successfully demonstrated on a laboratory, pilot, and precommercial scale for various wastes, including radioactive and hazardous wastes and MSW. The process includes several stages. In the first stage, the feedstock is desorbed at temperatures of 600–1100°F under conditions where oxygen is below 3%. In the second step, the gas products are mixed with excess superheated steam to complete the reforming reactions to produce a synthesis gas.

Different physical configurations are available for the reactor including a drum feed evaporator for batch process or a heated screw evaporator suited for shredded dry active waste, thick slurries, and ion exchange resins. Duratek has previously operated a fixed-based drum feed evaporator steam reforming system in Oak Ridge, Tennessee, and has a mobile system in Kingston, Tennessee. Additionally, its licensee (Ishikawajima-Harima Heavy Industies Co., Ltd., Yokohama Engineering Center, Nuclear Fuel Cycle Project Department) operates laboratory, pilot, and precommercial systems in Japan. Duratek is informally cooperating with Technip to introduce large-scale steam reforming equipment into one of the Technip pyrolysis facilities. The Duratek system has also been used in feasibility studies conducted in conjunction with the Intellergy Corp.

Before developing the steam reforming process, Duratek (then GTS Duratek) was working with the Proler pyrolysis process, which was originally developed by Proler Environmental Services and then sold to Schnitzer Steel in the mid-1990s. Under terms of the agreement, Duratek integrated a cyclonic vitrifier with the Proler kiln. A pilot plant was constructed in Houston and used to demonstrate the combined cycles ability to treat Swiss Auto Shredder Residue (called RESH in Switzerland). Although successful, the process was never implemented in Switzerland, and the Houston facility was closed in 1998. Although the company remains interested in applications for the technology, it reportedly is no longer actively marketing the process. Duratek is informally cooperating with Technip to introduce large-scale steam reforming equipment into one of the Technip pyrolysis facilities.

Organic Power (Oslo, Norway; company is now out of business)

This process is a modular CHP unit, using a downdraft FB gasification reactor. Marketed in Norway, South Korea, and Denmark, it has several plants online, the smallest having a capacity of 3300 TPY. It can accept a wide variety of wastes, from wood waste to industrial wastes. It has been used to provide in-house heat to plants.

Organic Power technology is based on a threefold process: the pyrolysis and gasification of solid waste and biomass and the combustion of the process gas produced. The feedstock is automatically batch-fed into the closed feedstock silo through hydraulically operated gates. Gasification occurs at the bottom of the silo. By accurate and automatic control of the air supply to the primary chamber, the required gasification is achieved. Completely burned out ash and slag is pushed out through the bottom. The low-calorie gas produced in the primary chamber flows into the secondary chamber, where secondary air is added to support the complete combustion of the low-calorific flue gas. The temperature in the secondary chamber is set to 1560–2010^{o} F before the gas flows into the cyclone-shaped tertiary chamber.

Remaining unburned fractions are completely burned out, and any remaining heavy particles in the fly ash are separated out. Leaving the tertiary chamber, the hot flue gas is cooled down in the flue gas-boiler where either hot water or steam is generated. The thermal energy may be used directly for heating purposes or to generate electricity through steam turbines. Before the flue gas is discharged through the chimney, it passes through a filter system assuring low emission values.[138]

Table F-7. Organic Power Facilities[139]

No.	Location	Capacity	Start-up	Gas Utilization
1	Nordmore BioEl (Norway)	-	2000	2.3 GWh of hot water for heating network
2	Boseong City (S. Korea)	20 TPD	2001	7 GWh of hot water for heating network
3	Elverum Fjernvarme AS facility (Norway)	10k TPY	2002	4MW / 24 GWh of hot water for heating network
4	Espedal Handelsgartneri (Norway)	12 kTPY	2002	4MW / 24 GWh of hot water for heating network
5	Nakskov (Denmark)	-	2003	12 MWth for heating
6	Gyeryong City (S. Korea)	6 kTPY	2003	2 MWth for heating
7	Haenam City (S. Korea)	6 kTPY	2003	2 MWth for heating
8	NTE facility (Norway)	6 kTPY	-	11 GWh of steam

Energy Products of Idaho (Coeur d'Alene, Idaho)

EPI offers two fluidized bed technologies for use in the conversion of waste materials to energy. The first is atmospheric fluidized bed gasification and the second is fluidized bed combustion. Both technologies are fully commercialized.

EPI is a technology company and does not operate a landfill or transfer station, but the fuels/feedstocks used in EPI systems include processed MSW (RDF), wood, agricultural wastes, municipal sludge, paper sludge, coal, tanker sludge, animal wastes, industrial wastes, and others. More than 250 fuels and mixes have been used in EPI systems. EPI can utilize any combustible waste as fuel. This includes non-recyclable paper and plastics, urban wood wastes, construction and demolition (C&D) wastes, the organic fractions of MSW, animal manure, and any agricultural residues or yard wastes. For EPI systems, MSW is the primary feedstock, which is processed by others into RDF. Therefore, EPI systems are located at facilities with an associated MRF and at facilities where the waste is brought in from a remote MRF facility.

EPI has designed and built 81 systems, which are in operation around the world. Of the 81 systems, 4 are gasifiers and 77 are combustors.

The following EPI energy systems operate on RDF through a materials recovery facility:

1. Northern States Power Unit 1, La Crosse, Wisconsin.
2. Northern States Power Unit 2, La Crosse, Wisconsin.
3. Steam Plant #6, City of Tacoma, Tacoma, Washington.
4. AREA, Ravenna, Italy.

5. Bergamo Ambiente e Servizi Bas, Bergamo, Italy.
6. CCT/EuroEnergy Group, Massafra, Italy.

The following plants operate on materials diverted from landfills:

1. Delano I and Delano II—Urban wood waste.
2. Madera—Urban wood waste.
3. BFC Gas—Industrial wastes.
4. Bervard—Industrial.

The fuel for use in an EPI fluidized bed gasifier must be shredded to <3" in any direction. The optimum moisture content for gasification is <30% moisture. Wetter fuels may be gasified, but this will result in a decrease in the energy value of low Btu gas (LBG).

The fuel for use in an EPI fluidized bed combustor must be shredded to <4" in any direction and 90% should be <3". EPI combustion systems are designed to handle fuels with moisture content ranging from 5% to more than 60%.

An EPI fluidized bed gasifier or combustor produces two dry waste streams and two waste water streams.

The dry streams are:

1. The noncombustible material, such as rock, metal, glass not removed when processing the MSW into RDF, and small amounts of agglomerated bed media. These are discharged from EPI's proprietary bed cleaning and reinjection system.
2. Fly ash, which exits the fluidized bed and is removed at various points including ash drops from the boiler and economizer. The majority of ash is removed by a baghouse just prior to exhausting from the stack.

The liquid streams are:

1. The boiler blowdown. The boiler blowdown water is neutralized and discharged to the municipal sewer system.
2. Blowdown from the cooling tower. The blowdown from a cooling tower is treated water, which is neutralized and discharged to the municipal sewer system.

Thermogenics Gasification Process (Albuquerque, New Mexico)

Based in Albuquerque, New Mexico, this company has developed a directly heated downdraft gasifier that is continuously fed and air-blown. It was designed specifically for MSW and can handle loads from 0.5 to 3 TPH. Thermogenics has reported a total of three commercial units built.

Thermogenics's market strategy is to create alcohol fuel from the syngas, collaborating with Power Energy Fuels, Inc. Specifically, Thermogenics and Power Energy Fuels wish to create Ecalene, an alcoholic mixture of methanol and C_2—C_5 saturated alcohols. Ecalene will be marketed as a high-octane blending stock and oxygenator for automotive fuels. Thermogenics and its partners have purchasers posed and ready for the product as soon as they start production. Thermogenics is currently planning a demonstration tour of California with their trailer-mounted system.

ThermoEnergy: STORS & TIPS (Richmond, Washington) [This company responded to the survey and provided literature.]

Thermoenergy's Integrated Power System (TIPS) is being marketed in coal gasification. It recovers energy from the water in the process gases and recovers liquid carbon dioxide. However, its process is not clear.

Two other systems have been developed by Thermoenergy. The Sludge-To-Oil Reactor System (STORS) converts wastewater to bio-oil or char with a CV resembling medium grade coal (5,000–10,000 Btu/lb). One demonstration facility in Colton, California, is operating at 5 million gallons per day. The facility integrates the company's Ammonia Recovery Process (ARP) and produces the high-energy fuel from the STORS and fertilizer from the ARP. The facility runs on raw, digested, and waste-activated sludge.

Waste to Energy (Hampshire, UK)

Waste to Energy, a.k.a. Ventec, manufactures and markets a down-draft modular fixed-bed gasification system operating at approximately 2190^o F. Focusing on sewage sludge, they have collaborated with Anglian Water, a municipal water utility, to start a sewage sludge treatment facility in Broadholme, England. This process combines a dryer, a gasification unit, and a CHP unit to help Anglian Water process 1,200 tons per year of dry sludge while generating 0.25–0.33 MW for the facility.

Waste to Energy has also contracted out to the British Leather Corporation (BLC) to process the waste leather into energy. Also, the ash content from the process seems to be suitable for recycling since it has a significant amount of chrome, which is used significantly in leather manufacturing.

International Environmental Technologies, Inc. (IET)/Entech Renewable Energy Systems (Heathfield, UK)

IET markets the Entech technology in the U.K. and claims that it can handle a variety of wastes, from RDF and MSW to animal waste and hazardous materials. The material is fed into a gasification chamber running at 1020^{o}F. The process gas is then fired and the heat is gleaned for either heating or electricity. The gases are then cleaned according to EU requirements. IET reportedly has one prototype and several other facilities that have either failed to receive permits or have been shut down since beginning operations.

Reattori Gassificazione Riffiuti (RGR) Ambiente (Verona, Italy)

RGR was founded in 1993 to develop and market new gasification plants. The kiln operates at 2730^{o}F and is fed via the hopper. From the gasification chamber, the gases are quenched in a heat exchanger and burned in a boiler to produce steam.

The first pilot plant was dismantled in January of 1998 due to design problems. However, due to its experience with the prototype, the RGR team redesigned the plant and patented the new process in Italy in 1999. Another pilot plant was constructed with a capacity of 880 lb/hr in Italy and whose syngas produced a CV of 247 BTU/scf..

Industrial Processes/Technologies

The technologies under this category are some of the most widely utilized technologies, but may have had only limited use in processing MSW. In the case of Lurgi, these technologies are integrated as part of other MSW related projects.

Texaco

Texaco's Gasification Process (TGP) is an entrained-bed noncatalytic partial oxidation process in which carbonaceous substances react at elevated temperatures and pressures. This produces a gas containing mainly carbon monoxide and hydrogen. The resulting synthesis gas can be used to produce other chemicals or be burned as fuel. The TGP processes waste feedstocks at pressures above 20 atmospheres and temperatures between 2000 and 2800º F.

Waste feedstocks may include organic and inorganic contaminated soils, sludges and sediments; chemical wastes; and petroleum residues. Slurried wastes are pumped to a specially designed injector mounted at the top of a refractory-lined gasifier. The waste feed, oxygen, and an auxiliary fuel, such as coal, react and flow downward through the gasifier to a quench chamber that collects the slag. A scrubber further cools and cleans the synthesis gas.

The technology was demonstrated at the Texaco Montebello Research Laboratory, South El Monte, California, in January 1994. It uses a mixture of clean soil, coal, and soil from the Purity Oil Sales Superfund site located in Fresno, California. The mixture was slurried and spiked with lead, barium, and chlorobenzene. Forty tons of slurry was gasified during the three demonstration runs. Analysis of the dry synthesis gas revealed an average composition of 37% hydrogen, 36% carbon monoxide, and 21% carbon dioxide. Organic contaminants register < 0.1 ppm, except for methane (55 ppm). The DRE (destruction and removal efficiency) for the VOC spike was >99.99%, and the heavy metal spikes in the ash slag met the toxicity characteristic leaching procedure (TCLP) criteria.

Shell

Shell's Gasification Reactor (SGR) was first produced in the 1950s, primarily concerned with the gasification of heavy petroleum refinery residues. Operating between 2370 and 2730^{o} F and at pressures of up to 69 atmospheres, the carbon conversion efficiency is about 95 percent with a methane slip of close to 1%. The only byproduct is water. From there, the syngas is fed into the heavy paraffin synthesis chamber, where liquid hydrocarbons are synthesized. Further down the process, more synthesis takes place. Separation of paraffins takes place with Heavy Paraffin Conversion creating middle distillates.

ThyssenKrupp Uhde (Dortmond, Germany) [This company responded to the survey and provided literature.]

Uhde is one of the larger producers of gasifiers worldwide. Uhde's experience in gasification extends over a period of 60 years and includes more than 100 gasifiers based on five different technologies. Uhde is heavily involved in coal gasification, but also has developed technologies for a range of other feedstocks including MSW, dried cattle blood, and chicken litter.

The PREssurized ENtrained FLOw (PRENFLO) process is one of the gasification technologies used by Uhde that was developed through a joint effort with Shell. In this process, the feedstock is fed along with oxygen and steam into the lower part of the gasifier. This reactor operates at approximately 25 atmospheres and produces a syngas at approximately 2910^{o} F that is subsequently cooled to 1470^{o} F and then further cooled to 715^{o} F. The inorganic materials are melted in the high-temperature bottom portion of the reactor to form a slag.

This process is used in the world's largest IGCC power plant in Puertoollano, Spain (318 MWe). Uhde is also engaged as an engineering contractor for Shell gasification technologies in other projects worldwide including in the U.S., Italy, India, China, Spain, and the Netherlands. Uhde has also been heavily involved in the development, design, and operation of the Texaco coal gasification demonstration plan in Oberhausen, Germany, which has been in operation for more than eight years. Udhe also designed and constructed the High Temperature Winkler (HTW) fluidized bed gasification process, which was operated at a pilot scale in Wachtberg Germany, and then at a commercial scale in Berrenrath, Germany. The Berrenrath plant has gasified more than 3.3 million short tons of brown coal since 1986 with average operation exceeding 8,000 hours per year.

Krupp-Uhde PreCon process [140,141,142,143,144,145,146,147,148]

The PreCon1 process is a modular fluidized bed gasification (FBG) technology that utilizes an air- or oxygen-blown HTW gasification process that can operate at pressures from ambient up to 30 atmospheres (Figures F-5 and F-6). The process was developed as part of a joint effort by Krupp Uhde GmbH and Rheinbraun AG of Germany. The process can be used with a variety of feedstocks including ASR, contaminated coke, lignite coal (<1 cm fines), MSW, postconsumer plastics, and sewage sludge. The feedstock is initially screened to remove scrap metals and dried to <10 wt.% moisture. The producer gas formed during gasification can be used in a boiler, gas engine, or turbine (including GTCC) as well as possible use in blast furnaces or as syngas.[149,150,151,152] A melting module for ash and filter dust vitrification is optional.

The HTW gasifier (Figure F-6) was originally developed as Atmospheric BFB (ABFB) technology by Rheinbraun AG between 1975 and 1997 [153,154,155,156,157,158,159,160,161,162,163] for pressurized oxygen and steam-blown coal gasification.[164] The process operated at 1472-1832ºF and a pressure of about 10 atmospheres.

In 1979, Rheinbraun built and operated a 25-40 TPD pilot lignite-fueled gasifier in Wachtberg-Frechen, Germany. A pressured (25 atm) gasifier with a 30 MWth, 160 TPD capacity subsequently went into operation in 1989. A 30 TPH oxygen-blown co-gasification demonstration plant operating at 1742º F and 10 atmospheres successfully ran from 1985 to 1997 in Hürth-Berrenrath, Germany, utilizing ASR, contaminated coke, pretreated MSW, six postconsumer plastics, and sewage sludge with lignite. This plant produced 300 Mm^3 (about one billion cubic feet) of syngas annually for methanol production at the Union Kraftstoffe Wesseling works of DEA Mineraloel AG (DEA) while in operation.[165,166,167,168,169,170,171,172,173,174,175]

Since 1988, a pressured (13 atm) oxygen-blown gasifier by Kemira Oy has operated in Oulu, Finland, with a 90 MWth and 27 ton-per-hour capacity (60% peat and 40% wood waste) for the production of syngas for ammonia synthesis.[176,177] Currently, a 20 TPD MSW-fueled gasifier operating at a pressure of 1.5 atm and using an ash vitrification module is operating at Sumitomo Heavy Industries Ltd (SHI)'s Nihama facility in Sikuku, Japan.[178] A 1 tph atmospheric gasifier also exists at the RWTH Aachen campus in Germany.[179]

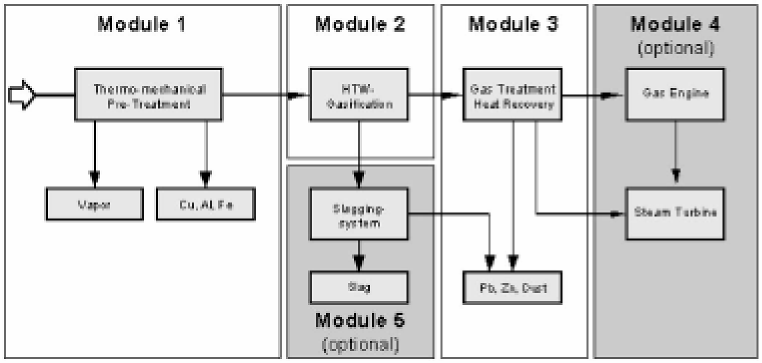


Fig. F-5. Schematic Concept of the Krupp Uhde PreCon Process.[180,181]

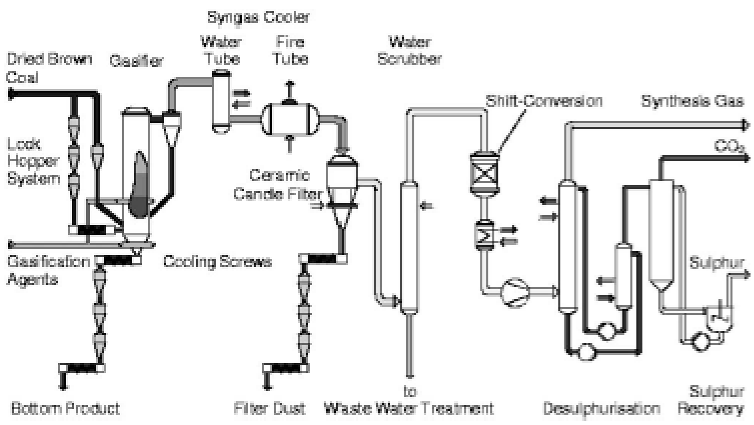


Fig. F-6. Flow Diagram of the HTW Demonstration Plant.[182,183]

Lurgi Processes

A subsidiary of the German engineering company Metallgesellschaft AG, Lurgi has attempted to broaden the scope of their projects by supplying a variety of systems for the wide range of wastes that have significance. Lurgi's gasifier technologies include:

- FB gasifier (non-slagging).
- FB gasifier/British Gas Lurgi gasifier (slagging).
- Fluidized Bed Gasification (CFB).
- Entrained Flow Gasification (Destec Gasifier).
- Lurgi Residue (LR) thermal gasification process.

Lurgi also has licenses for the Ebara fluid bed waste technology for Europe (purchased through Holter ABT) and the Pyromelt technology.

PyroMelt Technology

The PyroMelt process was developed by ML Entsorgungs- und Energieanlagen GmbH (MLEE). It combines pyrolysis and slagging combustion.[184,185,186] Recent information indicates that this process is not actively being promoted, but it is included here for completeness.[187] The process is suitable for different kinds of wastes such as MSW, hazardous waste, postconsumer plastics, and ASR light fractions that are shredded to<15 cm before processing. The process is shown in Figure F-7. The waste is pyrolyzed in a drum at 2192º F. The majority of the pyrolysis gas is combusted with air to heat the drum while the flue gas and the remaining pyrolysis gas are directed to a HRSG for steam production.

Prior to combustion, the pyrolysis gas is subjected to multiple scrubbing steps using the recycled medium and light fractions of the pyrolysis oil. During scrubbing, the gas cools from 932–1112º F down to 248–302º F upon leaving the drum. Sorbents are also added during processing to provide in-situ desulfurization and/or dehalogenation to simplify flue gas cleanup. The char is cooled from 932–1022º F to about 122º F and subsequently sorted and shredded to <5cm. Ferrous and non-ferrous metals are also separated. The char is combusted with the dust and heavy pyrolysis oils in a Kubota-Surface-Melt-Furnace (KSMF) reactor[188,189,190,191] using preheated air. In the secondary furnace chamber, the exhaust gas is subjected to oxygen enrichment of up to 6 vol.% vitrifying the ash containing (heavy) metals at about 2462 ºF. The resulting slag is then water quenched and granulated.

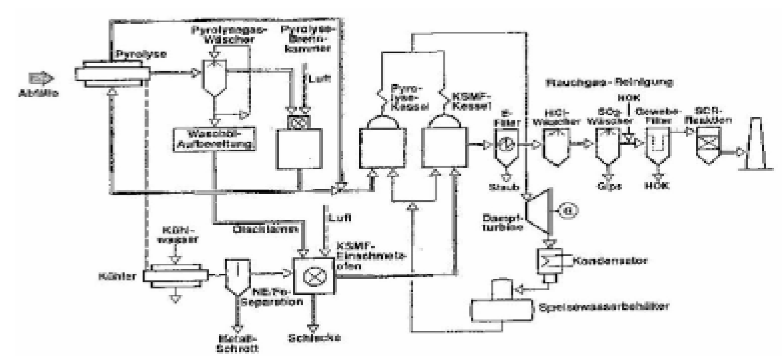


Fig. F-7. Schematic of the PyroMelt Process[192].

Noell-KRC conversion process [193,194,195,196,197,198,199,200,201,202,203,204,205,206,207,208,209]

The Noell-KRC conversion process is an entrained flow gasification process developed by Noell-KRC Energie- und Umwelttechnik GmbH, which is now part of Babcock Borsig Power Group. This is a two-step thermal treatment process where the waste is pyrolyzed at about 1022º F in an externally heated rotary kiln for about 1 hour and subsequently gasified in a slagging entrained flow using oxygen at flame temperatures of 2552–3632ºF and 2–50 atmospheres (Figure F-8).

Besides MSW, other feedstocks (industrial waste slurries, dried sewage sludges, and pulverized coal) may be co-gasified. Apparently, the process is being marketed primarily for industrial and hazardous wastes.[210] The resultant gas is of medium heating value and can be used as a syngas or combusted in a boiler, gas turbine, or engine.[211,212] A part of the clean gas is also typically used to heat the kiln. The slag is water quenched upon leaving the gasifier and granulated for use in the construction industry. Energy flow rate in the feedstock is about 38.6 MWth (35.9 MWth from MSW and 2.8 MWth from sewage sludge). Approximately 5.1 MW of electricity is produced by burning the product gas in a gas engine generator set. This is equivalent to an overall conversion to electricity efficiency of about 13% efficiency which is not unheard of for such small-scale applications.

A refractory lined/water-cooled 5 MWth entrained flow gasifier has been operating since 1979 in Freiburg, Germany. This plant operates at 26 atmospheres, has a capacity of 0.5 ton per hour capacity, and has been successfully tested on different kinds of wastes (refinery and chemicals residues, waste water, and spent solvents). A reactor at the Sekundärrohstoff- Verwertungszentrum Schwarze Pumpe GmbH (SVZ) site began operation in 1984 for the production of 'town gas' from salt-rich lignite.

This facility was converted in 1991 for the processing of contaminated oils, tars, solvents and solids containing wastewater. Methanol is synthesized and integrated gasifier combined cycle (IGCC) us utilized for power production. Noell also has a 13 tons-per-hour entrained flow gasification plant in Middlesbrough, U.K. This plant treats nitrogen containing residues from the Seal Sands caprolactam plant of BASF plc.[213,214]

From 1996 to 1999, A 40,000 TPY pyrolysis plant also operated at the Salzgitter Pyrolyse GmbH smelting works site to treat hazardous materials (spent oils and PCB-containing waste). A 10MWth facility with up to a 1,550 lb-per-hour capacity began operation in Freiberg for treating (sewage) sludge and other residues and slurries. A demonstration plant that processes municipal solid waste (110,000 TPY) and dewatered sludge (16,000 TPY)started operation in Northeim, Germany in 1995.[215,216,217,218]

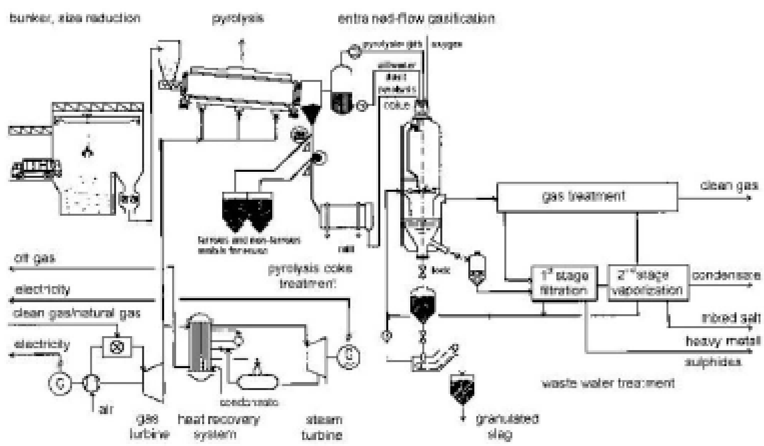


Fig. F-8. Scheme of the Noell-KRC Conversion Process.[219]

Gasification of Wood/Agricultural Waste

As with pyrolysis, a number of gasification processes are generally applied to wood or agricultural waste, but could be applied to MSW. Some of the gasification technologies in this category are presented below.

The BCL/FERCO technology [220,221,222,223,224,225,226,227,228,229230,231,232,233,234,235,236] [This company responded to the survey and provided literature.]

The BCL/FERCO process is an autothermal two-vessel gasification process that was developed by Battelle's Columbus Laboratory (BCL) and licensed to Future Energy Resources Corporation (FERCO) in 1992. The Battelle gasification process is a two-stage indirectly heated atmospheric pressure circulating fluidized bed system. It is designed to gasify wood, biomass, and potentially MSW components, using steam in a fluidized heated sand bed (Figure F-9).

The atmospheric CFB gasification is carried out in a reactor using steam at about 1526º F. Hot medium-energy gas leaves the gasifier with the sand and char. The sand and char is separated from the gas and flows to the circulating fluidized bed combustor where the char is burned in air reheating the sand, and providing heat to generate steam, and dry feedstock. The hot sand circulates to the gasifier reactor where it provides the heat for gasification. Because steam is used to gasify the biomass the product fuel gas is free of nitrogen and has a heating value of 350-485 Btu/scf, using wood as the feedstock. The gas can be utilized in an engine, gas turbine if suitable gas cleaning is provided. Depending on internal plant power requirements, and the type of prime mover employed, overall efficiencies of 25% to > 40% are achievable.[237]

This process has been demonstrated primarily with wood chip feedstock, but it has also been tested with RDF. Battelle has a small research unit that has been operating since 1977 and has accumulated about 20,000 hours of operation using different fuels (wood chips, bark, sawdust, RDF, and poplar as well as switchgrass).[238,239,240,241] For RDF, the unit has a throughput of between 0.22 and 9.1 Mg/d of dry RDF.[242,243,244] The longest continuous operation with RDF was approximately 100 hours at 10 TPD. It was concluded from these studies that higher throughputs exceeding 19.5 Mg/h m^2 could be accomplished.

Figure F-10 shows a mass and energy balance for Battelle's indirectly heated gasifier based on figures reported in a study by the National Renewable Energy Laboratory.[245] The process was demonstrated by BCL/FERCO at a wood-fired power plant of the Burlington Electric Department in Burlington, Vermont, under support from the U.S. Department of Energy (DOE). The plant has a 200 TPD capacity and was designed for the installation of a gas turbine. Though the gasifier operated successfully, demonstration funding was exhausted before the gas turbine was installed.

An energy firm in the UK (Peninsula Power) is planning to build a 23 MWe (net) BIGCC facility using the FERCO gasifier and a Siemens Cyclone gas turbine. Fuel will come from a consortium of energy crop growers (short rotation willow coppice and miscanthus) and local forestry operation wastes. The project cost is reported to be $70 million of which $20 million is a renewable energy grant award from the government. The project is in the permitting stage.

A project in Forsythe County, Georgia is under development by Biomass Gas & Electric, LLC. The project will be located adjacent to a CD&D landfill Most of the fuel will be clean wood wastes supplied by the landfill operator. Supplemental fuel will be saw mill wastes and herbaceous crop residues. A FERCO gasifier has been selected. Initially, the gasifier will provide fuel for a steam boiler. Later plans call for installation of a gas turbine for combined cycle operation. The plant will consume 400 tons per day of fuel and produce approximately 20 MWe. The project has received zoning approvals and environmental permitting is underway. Power purchasing agreements are being negotiated. from the

A third FERCO gasifier project is being developed. This project will initially fuel a steam boiler and steam cycle with addition of gas turbines or reciprocating engines later. The project is obtaining zoning approvals. The fuel source was not reported.[246]

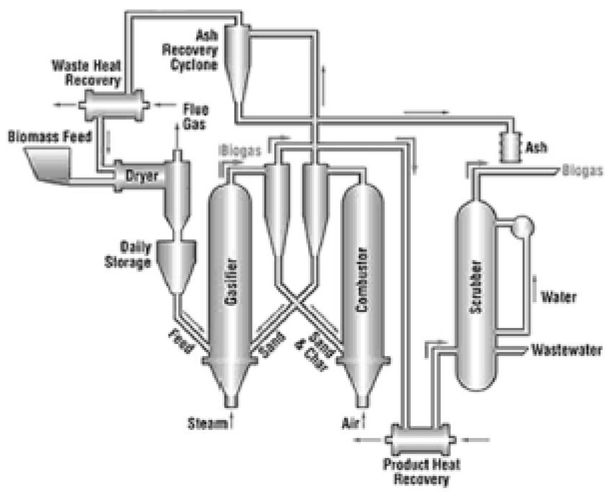


Fig. F-8. Schematic of the BCL/FERCO Allothermal CFB Gasification Process.[247]

Battelle Material/Energy Balance 1000 kg basis of RDF

Input		
	Material (Kg)	Energy (MJ)
	TO GASIFIER:	
RDF	1,000.00	1,969
H2O Liquid	290.33	0
Feed water	311.81	111
Subtotal	1,602.13	2,080
	TO COMBUSTOR:	
N2	1,735.40	
O2	461.30	
Subtotal	2,196.71	93

Heat Loss Summary
Heat Loss from Heat Exchange = 1.52 % of HHV
Heat loss from Gasifier = .21%% of HHV
Heat loss from Combuster = 0.37 % of HHV
Heat loss from Cyclones 0.52 % of HHV
Heat Loss from Piping = 1.3 % of HHV
Heat Loss from other = 0.26 % of HHV
Heat Loss Total = 4.27 % of HHV

Output		
	Material (Kg)	Energy (MJ)
	PRODUCT GAS:	
Ash	0.26	
N2	7.39	
CH4	76.25	
C2H4	77.96	
C2H6	4.68	
CO	305.42	
CO2	123.55	
H2	9.72	
H2O vapor	743.04	
Subtotal	1,348.27	1,792
	FLUE GAS	
Ash	60.26	
N2	1,207.39	
O2	45.60	
CO2	599.81	
H2O vapor	27.43	
Subtotal	1,940.50	293
	Ash	
H20	188.21	
H2	3.20	
C	163.55	
Subtotal	354.96	63
	Wastewater	
H20	266.14	
N2	0.76	
H2	0.47	
C	3.78	
Subtotal	271.14	21

	Material	Energy		Material	Energy
Total Input:	3,798.84	2,172.7	Total Output:	3,914.87	2,169.2

Fig. F-10. Material and Energy Balance for Battelle FERCO Process.

The MFU gasification process

Mitteldeutsche Feuerungs und Umwelttechnik GmbH (MFU), a subsidiary of GÄU Energie & Recycling GmbH of Germany, has developed a high-temperature oxygen-blown slagging gasification process[248] based on a cupola furnace.[249,250,251,252] The furnace is equipped with two levels of oxygen-burners (Fig. F-11)[253] and is ideal for high throughputs (2.5t/h or 30–40 GJ/h).

The process accepts a variety of feedstocks (MSW, wood and animal waste, TDF, ASR light fractions, sewage sludge etc.) that must be crushed and shredded to a 10–300 mm size. At the first burner, the primary gasification takes place at a temperature of 3632º F, which provides heat for the process. The product gas and the pyrolytic char subsequently move to a second burner stage where the char is combusted to a slag. The CO-rich gas (15%–24% H_2 and <1% CH_4) escapes in cross-flow between the stages and is subjected to CGC while the char latter leaves the reactor at the bottom together with any unreactive melted ash. For testing, MFU owns a 10,000 TPY pilot plant in Leipzig, Germany, with a 1.2 TPH throughput. A 6.5 MWth-wood-waste-fueled CHP plant is currently under construction in Rothenburg/Oberlausitz, Germany.

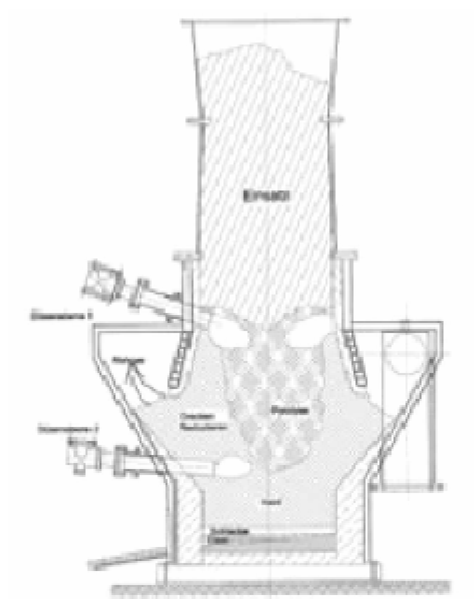


Fig. F-11. Cross section of the 2sv Gasification Reactor.[254]

Torftech [This company responded to the survey and provided literature.]

Toftech has developed a range of process reactor gasification technologies that have been applied to a number of industrial processes. The process reactors can be designed to handle a range of input materials and operate anywhere between cryogenic and temperatures to 2910^{o}F. The processes are particularly applicable to handling fine solids and irregularly shaped and mixed size solids, including micro-sized powders, sludges, and slurries.

The first commercial prototypes were installed in 1986. Currently 100 or more plants have been installed in various locations including Europe, North America, South America, New Zealand, Australia, China, India, and Japan. The applications include spice pasteurization, clay calcinations, dry scrubbing of HF from aluminum smelter off-gases, vermiculate exfoliation, and production of puffed rice breakfast cereal.

Torftech has two commercial or nearly commercial applications in the energy-to-waste area. One utilizes urban wood waste in Holland to pasteurize and dry cattle manure for sale as fertilizer. In this application, the TORBED reactor can handle a range of strangely shaped wood pieces—even hinges and door handles—while achieving a very high burnout of the organic material. Each of the two reactors can process 1 to 1.5 TPH of wood waste generating electricity.

Torftech is also commissioning a plant in India for the generation of energy from rice hulls. This plant was expected to be ready for operation in September of 2003. This plant utilizes a combustion temperature of 1520^{o} F will be capable of utilizing 1–2 TPH of rice hulls. By carefully controlling the combustion temperature, a 95% pure amorphous silica ash is formed. This can be used in other applications. In contrast, energy processors in Arkansas and California are producing more crystalline ash that is not usable and must be landfilled.

Others

The principal companies using these processes were not contacted directly, since they are either at a low level of commercial development or do not directly deal with or plan to deal with MSW. These include companies like Lurgi, Wellman, Thermogenics, JND, Global Energy, and Babcock Borsig Power that have shown some experience in the gasification market. Others, like McMullen, are at the design stage. The following information draws largely from the Juniper Consultancy Services report[255] and applicable websites.

Primenergy, L.L.C. (Tulsa, Oklahoma)

Primenergy's existing commercial operations are fed with biomass fuels of rice hulls and the waste from olive oil processing. At the Tulsa, Oklahoma, location, Primenergy has a commercial-scale demonstration gasification and energy generation installation. At that facility, multiple solid fuels have been successfully converted into energy, including engineered fuel from MSW.

For the conversion of MSW, the energy conversion process begins with an aggressive separation and sorting of the bulk waste. The separation should recover approximately 30% of the incoming waste for recycling even where curbside and commercial recycling programs are achieving up to 50% recycling rates.

This recycling is accomplished in a specialized MRF. Within the MRF, recyclables such as steel and aluminum are recovered at nearly 100% and additional paper, plastics, and organic materials are sorted for recycling. Nonflammable or potentially hazardous materials are removed from the waste stream. The recyclable materials, plastics, paper, aluminum, glass, copper, etc., are returned to centers to be recycled. The remaining material, mostly marginal paper and mixed plastics, is refined and processed into an engineered fuel. Compared with the municipal solid waste fed to incinerators, this fuel has a composition that is much more chemically consistent and has a higher fuel heating value. This eliminates the requirement for the use of supplemental fossil fuels such as fuel oil, propane, or natural gas.

After the preparation of the engineered fuel from MSW, the material is fed into the gasification process. Within the gasifier, process conditions are maintained to produce a combustible synthesis gas. The feed rate to the gasifier is controlled to maintain a preset energy demand, such as electrical output.

The hot combustible syngas evolved in the gasification process is then oxidized in a series of stages for the proactive control of NO_x. In the final oxidative step, the syngas is totally oxidized in a boiler, where the energy is recovered as steam. High-pressure superheated steam is directed to a condensing turbine that ultimately drives an electrical generator.

The company claims that with the application of staged combustion and air pollution control technologies, the proposed process will achieve emissions levels comparable to those of natural gas fired combined cycle power generation. The composition of the gasifier fuel feed is typical for engineered fuel from MSW.

Process wastes are comprised of gasifier bottom ash and fly ash. The bottom ash contains carbon and can be used as a supplemental fuel for cement kilns. The fly ash may be landfilled. There are no liquid discharges.

Although the process for the conversion of engineered fuel does not require co-feeding of other materials or the use of auxiliary fossil fuel, any normal biomass material can be fed to the gasifier. Other biomass materials may be co-fed from zero to 100%.

Based on the LHV (wet basis) of the engineered fuel feed and a gross electrical output of 18,547 kilowatts, the conversion efficiency is 21.7%.

This does not take into consideration the energy that is lost in the evaporative duty of the moisture content of the feed. Based on the available energy, i.e. the calorific energy net of the evaporative duty of the 18 percent moisture content, the conversion efficiency is: 22.4 %.

Wellman (Oldbury, UK)

Wellman has designed and supplied its updraft fixed-bed gasifiers for a variety of uses. The company has been in the gasification business for 70 years and has designed reactors for bituminous coal, lignite, and coke. Recently, Wellman has developed an updraft fixed-bed gasifier for wood-based feedstocks that generates 2.5MWe. However, the company indicates that it is interested strictly in renewable energy, not waste conversion, because its updraft technology is not designed for waste conversion. It also is developing a fast pyrolysis technology that is designed to produce 500 lb of pyrolysis oil per hour.

Renewable Energy Corporation (REC)

The Waterwide Close Coupled Gasifier was developed in the 1970s (originally as a food process heating source) and was revamped for waste-to-energy application in the 1990s. This process was licensed to REC, a company developed in Australia specifically to exploit the Waterwide technology.

REC has several hundred small-scale facilities scattered throughout Australasia, most dealing with crop and wood drying. Heat generated ranges from 2 and 10 MWth. REC has developed the gasification technology by recycling the flue gas and redesigning the flow of the feed to enhance the robustness of the gasification. The technology includes a redesigned chamber to reduce the fixed carbon count and self-cleaning mechanical grates that allow clinker control of the process when gasifying difficult fuels.

Gasification of Sludge

Some gasification technologies discovered focused mainly on the conversion of wastewater and sludge, but could be applied to MSW. Some of the gasification technologies in this category are presented below.

Chematur (Karlskoga, Sweden)

Chematur currently has three plants in operation, one in-house pilot plant, one plant in Kobe, Japan belonging to a licensee, and one commercial installation at Johnson Matthey, London, U.K.

Wastewater or sludge is, if necessary, pretreated (e.g. wet milling) to make it pumpable and then the pressure is increased to about 237 atmospheres. Feed slurry is preheated to about 720° F in the effluent phase and at startup in a gas-fired heater. The pressurized and preheated stream is fed to the pipeline reactor, and oxygen is added to start a very rapid and complete conversion of all organic material to carbon dioxide and water.

After about one minute reaction time, the stream is led to the heat exchanger to preheat the feed. The steam then goes to energy recovery. For example, cooling follows steam generation to release temperature, and a proprietary technology is applied to reduce pressure. The clean effluent is fed to a gas-liquid separator where CO_2 and some excess oxygen are separated. No NO_x, SO_x or dioxins are formed, which means that no gas cleaning is required. No chimney is required, since effluent gases are released at close to ambient conditions. Any solid inert material in the feed (for example, heavy metals) is precipitated as a fine grain, non-leachable ash in the clean sterile water phase.

MTCI steam reforming technology (Baltimore, MD)

The PulseEnhanced™ steam reforming technology was developed by Manufacturing & Technology Conversion International, Inc. (MTCI). The system combines a multiple resonance-tube pulse Helmholtz-type combustor with a bubbling fluidized bed steam reformer (Figure F-12).[256,257,258,259,260,261,262,263,264] The pulse-enhanced heater is immersed in the fluidized bed reactor and generates heat with and oscillating flow in the transfer tubes that results in turbulent mixing and a significant enhancement in heat transfer. The steam-blown autothermal gasification in the fluidized bed takes place at 1472–1562º F, and the resulting gas product is subsequently used for the production of steam that is used as the gasifying medium. The process can be used with a variety of semi-solid and liquid biomass and other waste feedstocks, including those with high ash, alkaline and heavy metals as well as Cl and S contents.

MTCI began development of the technology in 1984 using a 12 TPD pilot-scale reactor in Santa Fe Springs, California. [265,266] More recent testing has been conducted at a larger 50 TPD plant in Baltimore, Maryland, using sub bituminous coal as well as wood chips and wheat straw.[267,268,269,270,271]

A 181 TPD black liquor demonstration project is under way at Georgia Pacific's containerboard mill in Big Island, Virginia. The goal of this facility is to achieve 40 percent electrical efficiency. Inland Container Corporation of Canada conducted some tests with the technology in the early 1990s at its 25 TPD sludge mill processing facility in Ontario. A 5000-hour test was also performed using a 50 TPD facility at Weyerhaeuser's paper mill in New Bern, North Carolina.[272,273,274] A 300 TPD coal-fueled gasifier was also reportedly being built at the Fort Union mine in Gillette, Wyoming, to provide steam for a coal beneficiation process.[275]

Several other plants have also been built/operated in Europe. In Germany, two 1.3-ton-per-hour biomass projects are planned by EF Electro-Farming Energie- und Umwelttechnik GmbH to produce fuel gas for 1.9 MWe fuel cells of different designs.[276,277] A 5.5 MWe project of 5-ton-per-hour biomass capacity is planned in Vetschau, Germany, by a consortium led by ECS Energie Consulting und Service GmbH

(ECS) and EBU Energiebu¨ ro Umwelttechnologie GmbH (EBU). The objective is 25% electrical efficiency using a steam turbine.[278] MTCI reportedly sold two gasifiers of 60 TPD black liquor and 120 TPD distillery sludge capacity to India and a 1 ton-per-hour black liquor gasifier to Spain.[279]

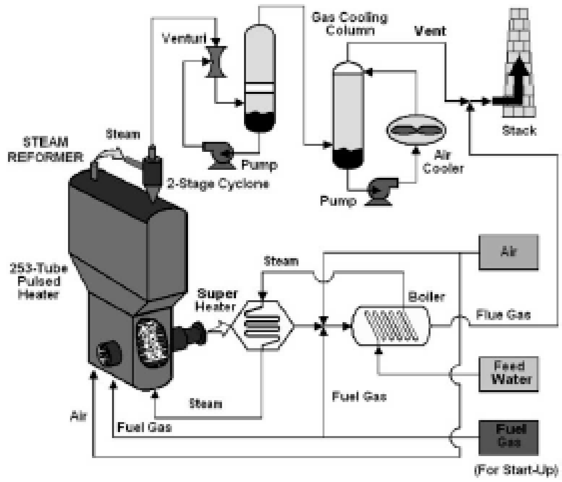


Fig. F-12. Schematic of the MTCI PulseEnhanced Steam Reformer Technology.[280]

Carbo-V-gasification (Frieburg, Germany)

The Carbo-V-gasification TM technology (Figure F-13) is a two step process developed by UET Umwelt- und Energietechnik Freiberg GmbH (UET).[281] In the first step, the dried and pretreated waste is gasified in an air-blown reactor called a Niedertemperaturvergaser (literally a "low-temperature carburetor") system at 572–662ºF for periods of less than 30 min. The resultant produces are a tarry gas and coke (8-10 mass% volatiles and up to 50 mass% carbon) that is subsequently milled.

In a second step, both products are gasified using preheated air or oxygen in a two-stage, entrained flow reactor—basically an entrained flow (see Figure F-13) at temperatures of 2552–2732ºF. The resultant gas is essentially tar-free and can be used for a 5 MW gas engine or used as a syngas, while the ash is vitrified. The resultant gas can also be further processed to produce a more energetic gas. by converting CO via the water-gas shift regime into H_2. UET erected a 1 MWth pilot plant of 660 lb per hour capacity in 1997-1998. In 1998–99, tests using wood chips, wood waste, organic refuse, sewage sludge, and hard coal were successfully performed for >3000 h. Currently, a 50,000 TPY biomass plant is under construction in Freiberg, Germany, to provide syngas for methanol production.

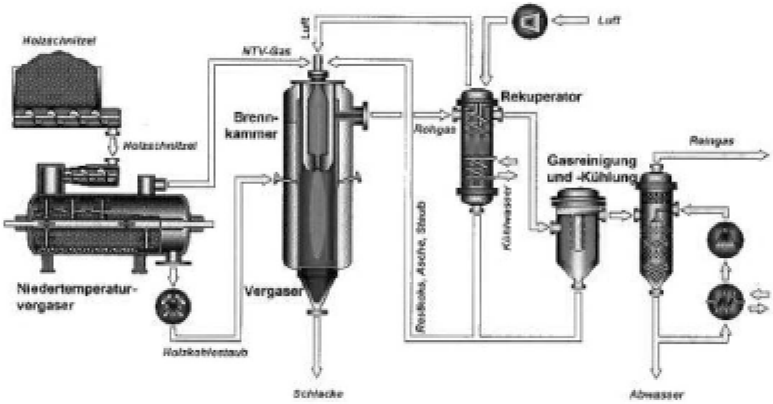


Fig. F-13. Schematic of the Carbo-V-Gasification Process.[282]

WGT Process (Hampshire, UK)

Waste Gas Technology UK has developed a gasification technology based on a cylindrical reactor operating in the temperature range of 1292–1652º F (Figure F-14).[283,284,285,286] The process is capable of using different kind of wastes including MSW, sludges, rubbers and plastics, wood and straw, and chicken litter. The feedstock is dried, mechanically pretreated to sort out incombustibles, and granulated to optimum-sized particles prior to entering the reactor. The gases from the reaction are quenched and cleaned of contaminants and then used in a gas engine, turbine, or possibly CCGT applications. The char is also combusted in a steam boiler.

WGT has a small 132-lb-per-hour pilot plant with a 55 kW diesel engine that has been operating since 1993 on different feedstocks, including RDF.[287] OSC Process Engineering Ltd (OSC), a licensee of the technology, also installed a 1,100-lb-per-hour demonstration plant that utilizes sewage sludge to produce energy for a dryer (Figure F-15). This plant was installed in 1998 for Welsh Water at Nash Water Works in South Wales. A 240-lb-per-hour sewage sludge processing plant was installed in 2000 in France under a WGT license.

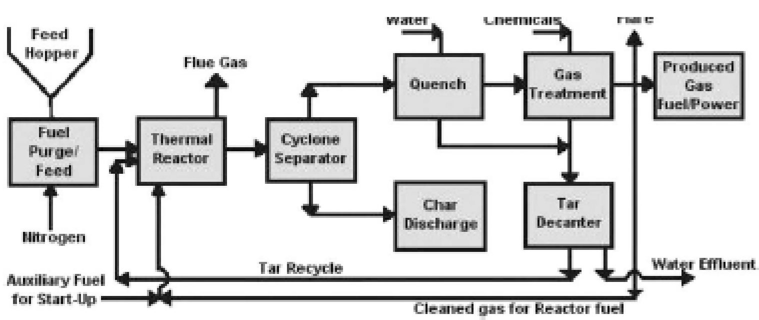


Fig. F-14. WGT Process Schematic.[288]

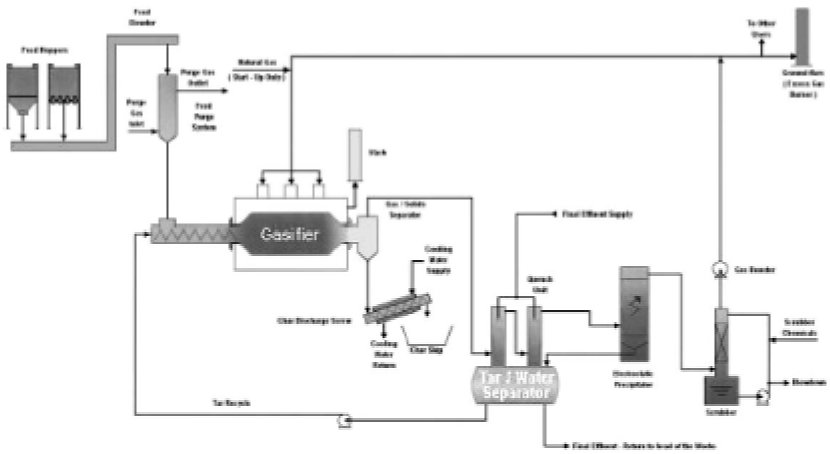


Fig. F-15. Schematic of a WGT Demonstration Plant.[289]

PRM Energy Systems

Originally intended for in-house heating, the vertical shell gasification unit is fed with rice hulls and is primarily used in agricultural projects. It has several plants running:

- 1993 Bernas Berhard (Malaysia)—produces 225 kWe and generates 12 MMBTU/hr of heat.
- 1995 Cargill Inc.—produces 75,000 lbs per hr of steam and 6.5 MWe. Also generates 160 MMBTU/hr of heat from 330 TPD of biomass.
- 1995 El Pelon (Costa Rica)—Generates 12 MMBTU/hr of heat and is designed for an addition of a 500 kWe generator.
- 1996 Riceland Foods Inc./Riviana Foods, Inc.—Produces 12 MWe and up to 100,000 lbs/hr of steam. Also generates 260 MMBTU/hr of heat.

A plant is under way in Italy, reportedly designed to generate 4.1 MWe from olive oil processing residue.

Primenergy is the marketer of the PRM technology in the USA and the Philippines. Grupo Guascor of Spain markets PRM for the European market.

KARA Energy Systems (Almelo, Netherlands)

KARA offers a large size-range of gasifier systems and can accept feedstocks from a variety of biomass sources, such as wood chips and agricultural residue. Their first pilot plant was built in the Netherlands. Since 1999, it has produced approximately 0.2 MWe from wood.

Currently, KARA offers systems that provide between 4 and 750kWe. Systems with capacity 10kW and below operate on charcoal, and those systems exceeding 10kWe area fueled by agricultural residue and wood. According to its website, KARA also provides thermal systems up to 15MWth.

JND Rotary Gasifier (Retford, UK)

JND, today a subsidiary of the A.J. Langley Group of companies, has supplied rotary kilns, dryers, calciners, and furnaces to various installations for 80 years. It has designed a 55,100 TPY facility capable of drying and gasifying MSW. Although JND is currently in negotiations to provide a facility to a city in Southern England, it has had no commercial plants built to date.

Host (Hengelo, Netherlands)

Host has developed a fixed bed gasifier as well as a FB gasifier for treatment of wood waste. A fixed bed unit has been demonstrated in the Netherlands; it is generating 200 kWe. Another demonstration facility is underway in Hengelo (Netherlands) for the FB gasifier; this is generating 8MWth. Typical electrical output ranges from 100 to 400 kW.

Heuristic Engineering—Envirocycler[290] (Vancouver, BC, Canada) [Company provided supplementary information]

The Envirocycler is a two-stage gasification/combustor unit that was developed to treat wet and dirty waste streams, specifically wood waste. The first gasification stage is an updraft design, followed by a double vortx cyclonic combustor that combusts the char. The technology has a history that dates back to the 1970s in the first generation applications. Different generations of this gasifier have been used in various applications since the 1970s, including a test program with RDF in New York in the late 1970s. Currently, Northwood Panel Board of Solway, Minnesota, is the only active facility using an Envirocycler, with waste heat being used to dry oriented strand board. This facility has two Envirocyclers with a combined capacity of approximately 5 MW. Other projects are also being developed in New Jersey for sludge, in Indiana for ASR combined with sludge, and in Malaysia for empty fruit bunch residuals from palm oil making processes.

CPL Biomass (Cheshire, UK)

Originally a division of British Coal, CPL developed an LFG utilization process and has contracted out to two Welsh Water sites in the U.K. for the drying of the biosolids. It is focusing on the renewable energy market and has plans to start DBFO projects that utilize gasification technology in different industry sectors.

Based on a horizontal rotary kiln, the technology is in the beginning stages. The company has 1 demonstration facility running a converted activated carbon regeneration kiln in Cumbria, U.K. It is currently rated at 1,100 pounds per hour and it is running on dried sewage sludge and wood chips.

Chemrec (Stokholm, Sweden)

Currently focusing on the paper industry, Chemrec is owned by Nykomb Synergetics AB and Noell Technologies. Originally designed for black liquor treatment for Kvaerner Pulp & Paper, the Chemrec process uses an entrained gasifier with an air mixture of 95% oxygen. The cleaned synthesis gas is used in a combined cycle power plant.

The demonstration plant in New Bern, North Carolina, runs at 300 TPD. Another facility in Sweden is being designed for a 550 TPD capacity. However, capital costs with this IGCC design remain a barrier to further development.

BG Technologies (Washington, D.C.)

BG Technologies is the North American licensee for the "ASCENT" gasification technologies, developed by Ankur Scientific Energy Technology, Baroda, India. This is a modular design that is geared toward rural communities in developing countries. Mostly small-scale facilities, they employ a fixed bed downdraft design. The process has been used on various biomass residues such as wood chips, coconut shells, rice husks, and sawdust. The main application of the installed systems has been for fuel production for small reciprocating engines that power water pumps. Some focus has been put on industrial heat and power, with modules ranging from 40 to 500 kW.

Babcock and Wilcox Volund (Kolding, Denmark)

The technology from this group has been developed to utilize straw and wood chips, but has also been tested on various other agricultural/forest wastes. Their demonstration facility in Denmark is a fully automated CHP design. Several units have been set up for various fuels in Denmark and have shown some economic stability. Babcock and Wilcox Volund is also looking at treating industrial wastes such as treated wood, ASR/EEESR, leather waste and PVC waste.

Babcock Borsig Power (Graz, Austria)

A large conglomerate of European power providers, Babcock Borsig has developed many co-gasification facilities. The company has focused on a fluidized bed design to co-fire coal and biomass. The company has two facilities that have been working with coal-to-energy facilities to provide useful heat for the process—one at Zeltweg and the other at Gussing, both in Germany. The Zeltweg facility has used wood-based fuels and even plastic as fuel. Gussing has yet to actually begin burning biomass.

B9 Energy (Northern Ireland)

B9 Energy has combined with Gengas Power Inc., the Swedish National Machinery Testing Institute (SMP), and Exergetics to develop a gasification technology. B9 has taken the SMP gasifier and modified it to create a CHP facility.

Wood chips are the fuel for the process, which is a downdraft gasifier SMP developed for road vehicles. The cleaned syngas from the process is fed into a spark-ignited engine to produce electricity.

The demonstration facility, located in County Armagh, Northern Ireland, has operated successfully since 1998. The facility produces 400kWth and 200 kWe, which is sold to the Northern Ireland grid.

Pacific Northwest National Lab (Battelle)

Battelle's high-pressure (204 atm) low-temperature (662 ^{o}F) catalytic gasification of wet biomass is fed slurry at 5%–10 wt% dry solids in water in a continuous-flow process. Carbon conversion to gas is at 99% or greater. The product fuel gas consists of methane (49% vol.), carbon dioxide(49% vol.), hydrogen (1-2% vol.), higher hydrocarbons (1-2% vol.), and a trace of carbon monoxide.

The process requires a pumpable slurry; which requires small particle size (minus 60 mesh) and high moisture (90% or more). The catalyst can be poisoned by certain inorganic components, such as sulfur; and mineral content at >1% can precipitate in the catalyst bed. Feedstock preparation is critical.

This liquefaction process is currently in pilot scale.

General Atomics (San Diego, CA)

The General Atomics is marketing supercritical water partial oxidation (SWPO) and supercritical water oxidation (SCWO) processes. Demonstration tests have been performed for SCWO of wood/plastics and SWPO of wood. A similar SWPO/SCWO process is possible using components of MSW, for example coprocessing a slurry of wood or paper with waste plastics. Wood/plastic size reduction, slurrying, and pumping have been demonstrated.

The SCWO/SWPO process can utilize any organic constituent in MSW, including food waste, paper, construction/demolition wood, yard trimmings, and plastic.

The SCWO process requires about 1.9 tons of oxygen per ton of wood/paper and plastic processed and about 0.7 tons of oxygen per ton of biosolids and grease processed. Electricity requirements are about 1.4 MW for the grinders, shredders, and feed pumps. The combustion air compressor (to heat the reformer) is assumed to be driven by the expanding gas from the first gas/liquid separator. Water requirements are about 8x the quantity of dry biomass solids as received(grease or plastic do not contribute to the water requirement). The water does not need to be clean. No natural gas or steam is required.

Liquid by-product from the system will be an aqueous stream and will contain ash and dirt from the biomass and chloride from chlorinated plastic. The chloride would be neutralized within the process to make dissolved sodium chloride. The ash/dirt is estimated to be about 4% of the biomass weight, or 1.6 TPD. The quantity of sodium chloride can be estimated from the chlorinated plastic fraction. The liquid by-product should be dischargeable to a municipal wastewater treatment works.

Improved Converter Inc. (Sacramento, CA)

The Advanced Multi-Purpose (AMP) converter is currently in the prototype phase awaiting funding of approximately $800,000 to perform prototype testing. Financial projections show that the AMP Converter is profitable above 300 tons/day with no fee charged for the waste or tire feedstock.

The AMP converter can treat all components of MSW with or without sorting and all components of tires. The AMP converter requires the incoming feedstock to be reduced to a size of less than approximately 10 inches in any dimension for a 10,000 TPD burden converter, or less than 4 inches for a 1000 TPD burden converter. Materials can be charged in a large range of moisture content, however, higher moisture contents will require higher ratios of petroleum coke or coal to be input.

Gas Technology Institute (GTI) (Des Plaines, IL)

GTI is producing gasification facilities that could run biomass at pressures ranging from atmospheric to over 27 atmospheres, suitable for gas turbines with appropriate cleanup systems.

GTI's technology is currently used in China for coal gasification with 8 150 TPD gasifiers operating in Shanghai. A pilot plant in Finland that can gasify 100 TPD of biomass is licensed to Carbona.

The GTI "Flex Fuel Test Facility" constructed in Des Plaines, Illinois, will be capable of operating with a wide variety of fuels for testing their performance during gasification and for determining the cleanup system requirements they will need to satisfy down stream end use specifications. The facility is capable of operating with air or oxygen at pressures up to 27 atm.

Eco Waste Solutions (Burlington, Ontario)

These are relatively small-scale systems, sized for 1 to 25 TPD. The process is a gasifier followed by a burning of the producer gas in a controlled combustion chamber. It typically operates on a 24-hour batch cycle. The material is enclosed in the gasification chamber and then heated (presumably with natural gas or propane) until enough energy is released by the gasification reactions to sustain itself. The system is marketed to small scale and/or remote waste producers. Units are installed in Canada, Alaska, Belize, and Hawaii.

Canada's Environmental Technology Verification (ETV) program has verified performance claims of Eco Waste Solutions for both municipal and biomedical waste.

Sacone Brookes (Lanarkshire, UK)

The Brookes gasifier is a batch design that mainly focuses on hospital waste and infectious wastes. It has several facilities in Scotland and claims to have several in the USA.

Samenwerkingsverband Duurzame Energie (SDE) / BIG-FiT

SDE has recently gotten involved in an ECN project entitled Biomass Integrated Gasification—Fischer Tropsch (BIG-FiT). As discussed in Chapter 4 of the report, Fischer-Tropsch is a synthesis process that may be used to synthesize long hydrocarbons out of syngas. This project team looked at the viability of producing fuels, especially diesel, from an integrated gasification and F-T system. Due to the vast amount of fuel production required, typical commercial-scale gasification systems will not suffice. The demonstration-scale BIG-FiT gasification facility will have a thermal input of 100kW to 3 MW. A full-scale BIG-FiT plant would have a thermal input of 200 MW.

Appendix G
Descriptions of Plasma Arc Processes from Survey Response

Discussion of Energy Production from Plasma Arc Facilities

Plasma gasification facilities require a large amount electricity to operate the plasma torch. The amount depends on the type of plasma torch, the reactor configuration, energy content of the feedstock, and amount of oxidant (air or oxygen) allowed in the reaction. Plasma arc technology may allow use of gas turbine combined cycle electricity generation technology which has higher efficiency than conventional steam power cycles. However, because of the high energy required by the plasma torch, overall plant electrical efficiencies are comparable to conventional solid waste combustion. Other high temperature slagging gasifier methods (i.e., oxgyen blown Lurgi or Emery Energy technologies) feeding gas turbine combined cycle (GTCC) power islands are expected to have similar or better overall electrical production efficiencies compared to plasma arc gasification with GTCC. The efficiency of a system proposed by Emery Energy using an air-blown dry ash gasifier feeding reciprocating engine gensets with steam bottoming cycle is competitive with the proposed plasma arc systems as well (see Table G-1A).

A recent report on emerging waste disposal systems prepared for the City and County of Honolulu (Towill-Corporation 2000)[291] reviewed plasma gasification of solid waste. The report indicates plasma arc gasifiers could be expected to generate 900 kWh of electrical energy per ton of refuse processed. However, only about 200 to 300 kWh per ton of feedstock would be available for export to the grid (about 22 - 33% net of generation).

For comparison, the H-Power solid waste-to-energy facility on Oahu, Hawaii, produces net electricity to the grid of 540 to 640 kWh/ton[292] and the SEMASS facility in Rochester, Massachusetts, exports 610 kWh/ton to the grid.[293] A proposal by Geoplasma LLC for the City and County of Hawaii indicates that a 375 TPD (or 100,000 tons per year) facility will generate 10.6 MWe gross but will consume 4.1 MWe internally leaving 6.5 MWe to export to the grid (equivalent to 415 kWh/ton input material).

RCL Plasma is another company offering plasma systems for treatment of MSW. Their system pyrolyzes the feedstock (no air or oxygen in the reactor) and the plasma torch requires 600 kWh of electricity per ton of MSW. Depending on the electrical generating technology used in conjunction with the RCL plasma process, the overall efficiency (net electrical energy divided by energy in feedstock) ranges from 0 to about 24%.

Table G-1A shows overall electrical efficiency, net energy per mass of input, and plant parasitic load for several proposed or operating plasma arc treatment facilities as well as two operating solid waste-to-energy combustion facilities. The data are compiled from elsewhere in the report and include information reported by companies in their survey response. Plant parasitic load for the plasma arc systems is high (39 to 46%) reflecting the high electricity requirement of the plasma torches. Overall efficiencies of proposed plasma facilities vary from 15 to 35% which brackets the efficiency for conventional MSW combustion (about 20%).

Table G-1A Plant and Technology Overall Efficiency Comparisons

Company	Facilty Information				Overall Electrical Efficiency (%)	Net energy per ton (kWh/ton)	Plant Parasitic Load (%)
	Technology	Status	Location	Capacity (tpd)			
Hitachi Metals	Plasma enhanced gasifier	Operating	Utashinai, Japan	165-300	*	413	46
GlobalPlasma LLC	Plasma enhanced gasifier	Proposed	Honolulu, HI	376	15	415	39
Recovered Energy Inc.	Plasma enhanced gasifier	Proposed	*	3000	29	804	*
RCL	Plasma pyrolyzer	Proposed	*	*	24	712	46
Solena	Plasma enhanced gasifier	Proposed	*	480	35	*	*
Emery Energy	Gasifier w/ recip engine genset and steam cycle	Proposed	*	650	27	736	5
H- Power	Combustion w/ energy recovery	Operating	Honolulu, HI	2000	19	540	13
SEMASS	Combustion w/ energy recovery	Operating	Rochester, MA	2700	22	610	14

Note; Plant parasitic load = (Gross power – Net power)
Generation technology for the Solena and RCL processes were stated or assumed to be gas turbine combined cycle.
Generation technology for the other plasma systems is not determined.
Generation for conventional combustion of MSW is steam Rankine cycle.
* Insufficient information supplied

Survey Response Descriptions

RCL Plasma (formerly Resorption Canada Ltd). *Ottawa Ontario*
RCL Plasma has been incorporated since 1973 and funded by the Canadian government to develop plasma based thermal processing of waste material. The company owns and operates a 200 kW (plasma torch size) demonstration facility in Ottawa. It appears the company has not built or operated any facilities other than the pilot plant in Ottawa. The company indicates that extensive third-party emissions testing has been done on the pilot plant under the auspices of the Ontario Ministry of Energy and the Environment; however, it has not provided copies of the emissions testing. RCL lists several patents awarded from at least nine countries (see Table G-1).

The technology can purportedly process a wide variety of waste streams from industrial, hazardous, and biomedical wastes to MSW. It is conceivable that the complete mixed waste stream could be processed through a plasma arc system, but removal of as much mineral matter (glass/ceramics and metals) as possible is preferred. Post-MRF residue would be an acceptable feedstock for MSW plasma conversion applications (complete removal of glass, metals, and inert mineral material before input to the plasma reactor is preferred). Shredding of feedstock will be necessary to provide a homogeneous mix to the feed handling system and a moisture content of 25% is preferred (mixtures that include green and food wastes would be acceptable).

Table G-1. List of granted patent numbers for RCL technology

Country	Patent Number	Year
Korea	294398	2001
US	6155182	2000
Germany	693 21 843 6	1998
Italy	19654BE/99	1998
France Ireland Spain UK	655083	1998
Australia	682313	1998
US	5280757	1994

A schematic of an early research plasma gasification system operated by RCL is shown in Figure G-1 (U.S. patent 5280757).[294]

A commercial scale facility would have different units for gas cleanup and energy or product recovery downstream of the reactor than those shown in the research system schematic in Figure G-1, but the plasma torch rector vessel would be similar (see Figure G-2).

The reactor vessel is a refractory lined structure with a means for injecting solid waste material into the reactor with a minimum of included air. Some air is injected at the torch to provide the gas for forming the plasma, though inert or burned exhaust gas can be used instead, which will contain little or no oxygen.

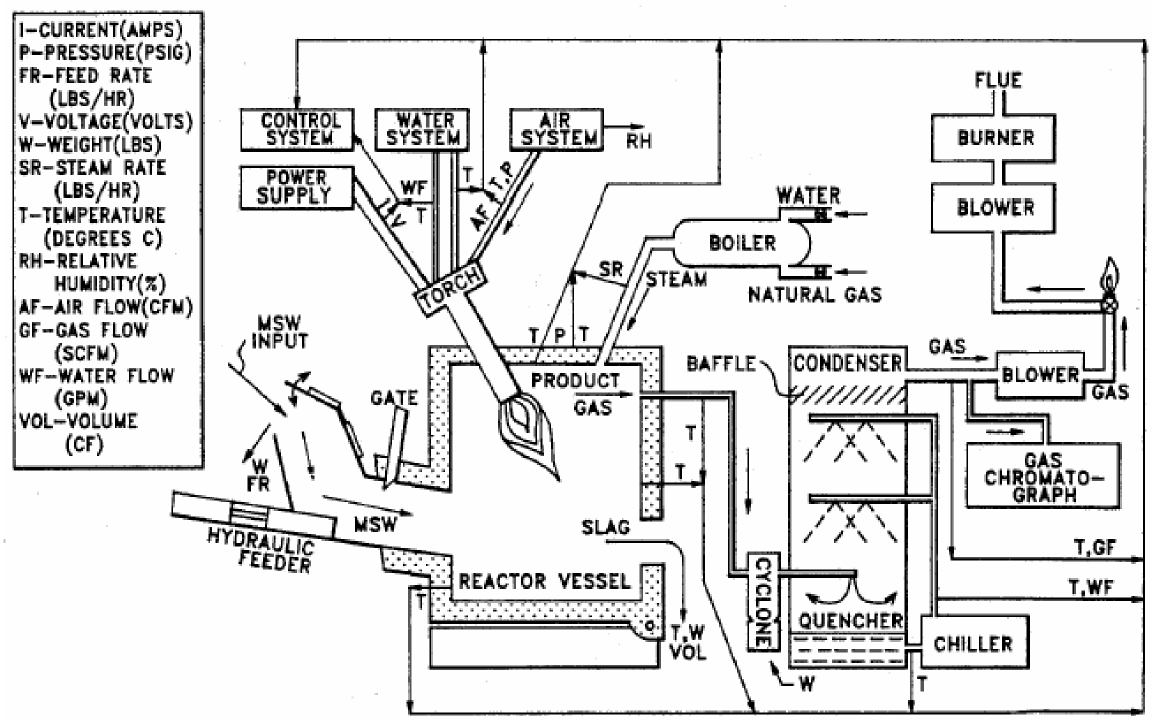


Fig. G-1. Schematic of RCL Research Plasma Gasifier. (adapted from US patent 5280757)

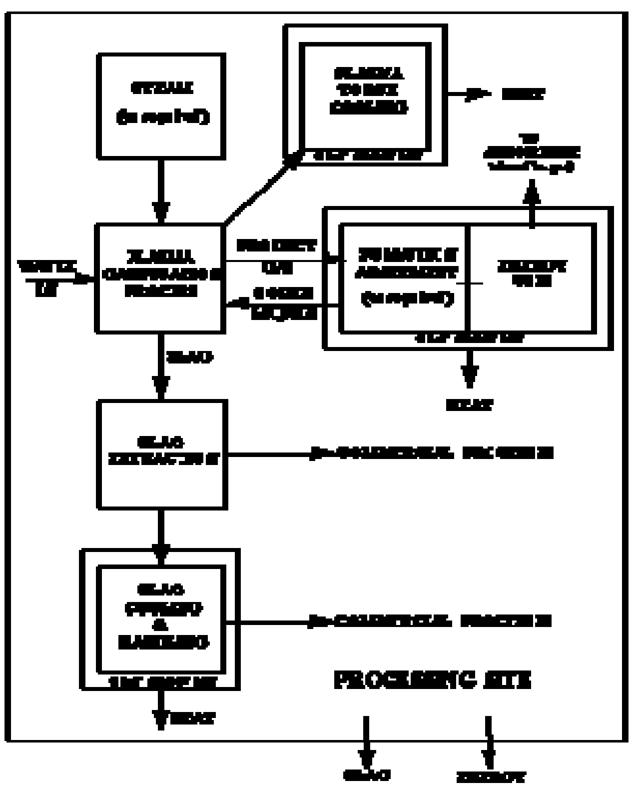


Fig. G-2 Schematic of RCL Plasma Arc Facility

Injected steam or moisture in the feed can supply reactant for the water-gas shift reaction that is an important steam gasification mechanism.

Downstream of the research reactor, the facility incorporated gas conditioning units in order to safely flare the product gas. A commercial facility would make use of the product gas rather than direct flaring.

Mass Balance

The mass balance for a plasma facility is fairly straightforward as practically all volatile compounds can be expected to leave the reactor as a gas. The amount of slag material is essentially equivalent to the ash (or mineral matter) content that is determined by simple proximate analysis.

RCL reports that a typical MSW would leave about 12% by weight as slag. This would be expected for a feedstock that has had most of the glass and metals removed.[‡] The remaining 82% of the feedstock, as well as the mass of input torch gas (either inert gas or air), will exit the reactor as a gas.

Depending on the moisture content of the feedstock, it may be advantageous to add steam to the reactor to ensure all carbon is gasified. The mass balance for the research reactor is displayed in Table G-2 (RCL patent, Carter, G. W., and Tsangaris, A., 1994). The feedstock is not characterized explicitly in the patent document but described as "refuse" or MSW with a moisture content of approximately 35%. The slag and cyclone ash recovered indicate the feed material had an ash content of about 11% which is consistent with the MSW material used in the survey response. The research reactor used air for the plasma torch gas and allowed a significant amount of air to enter the reactor through the fuel feed mechanism and viewing port.[§]

The air in the reactor will reduce the calorific value of the product gas because of oxidation and dilution (nitrogen in the air is unreacted in the product and serves as a diluent). A commercial facility will likely limit unwanted air in the reactor and use an inert gas for forming the plasma in order to improve the product gas quality.

Table G-2. RCL Plasma Gasifier Mass Balance
(average of two lab-scale experiments, source; US patent 5280757)

	Material	(kg)
Inputs	MSW (~35% moisture content)	193.7
	Air through torch	21.8
	Air - feeder and view port	114.1
	Total input	**329.5**
Outputs	Dry product gas out	276.1
	Water vapor in product gas	10.05
	Condensed Water	21.5
	Slag	21.4
	Cyclone Ash	0.45
	Total output	**329.5**

[‡] CA average disposed waste stream has ash content of ~ 25% (by weight). If all metals, glass, and minerals were sorted, the ash content would be about 6%.
[§] Typically, if the reactor is not designed to be pressurized, then it can be made more simply but may not be gas tight. To ensure no gas leaks from the vessel, it is operated at a slight vacuum (or negative pressure) so any leakage would be from the outside inward (air would come in). The slight vacuum is achieved by using an induced-draft fan at the exit of the process. The induced draft fan pulls gas through the complete system, which applies the small negative pressure at the reactor.

Energy Balance

The flow of energy in the RCL process is listed Table G-3. The information includes data reported in the survey response as well as from the company website.[295] For this energy balance, RCL assumed (or measured) the available energy in post-sorted MSW to be 10,900 MJ per ton. This figure is reasonable (though perhaps a bit low since most inert material had been removed). The energy consumed by the torch (2200 MJ) is a large amount that must be purchased as electricity or provided by onsite generation. Heat losses in the various unit operations and product streams are listed here as non-recoverable losses though some of the energy could be recovered depending on nearby opportunities for use of heat energy.

Table G-3. Energy Balance for RCL Plasma reactor (per ton of MSW and before use of product gas).

		Energy Component	Energy (MJ)
Input		MSW	10900
		Energy to Torch	2204
		Input Total	**13104**
Outputs	**Losses**	Torch loss	362
		Slag losses	89
		Vessel losses	60
		Other losses	1278
		Non Recoverable losses Total	**1789**
	Recoverable	Gas Sensible Energy	1291
		Producer Gas Chemical Energy (based on HHV)	10020
		Recoverable Total	**11311**
		Output Total	**13100**

The amount of electricity that can be produced from an amount of fuel gas depends on the technology used for the power generation as well as the energy in the gas. Table G-4 shows potential electricity production for the RCL plasma process using the synthesis gas in one of three electrical generation schemes; 1) fire the gas in a boiler to raise steam for use in a steam turbine (gas to electricity efficiency of 20%), 2) fire the gas in a reciprocating engine-generator set (gas to electricity conversion efficiency of 35%), and 3) fire the gas in a gas turbine combined cycle system after appropriate gas clean-up (gas to electricity conversion efficiency of 45%).

With simple gas furnace/boiler and steam turbine technology for electricity production, the plasma process can barely generate enough power to run the torch, leaving no electricity available for export sales. The most efficient electricity production that is feasible in the near term is to fire the fuel gas in a gas turbine combined with steam cycle (GTCC) which has an overall efficiency of perhaps 45%, accounting for compression losses and assuming the gas is cleaned to meet the strict requirements of gas turbines. Still, because of the high energy requirements for the plasma torch, the exportable electrical energy from firing the fuel gas in a GTCC amounts to about 700 kWhr per ton of feedstock, or an overall electrical energy efficiency of about 24%. This is comparable to the recoverable energy (and net efficiency) of conventional mass combustion units.

Table G-4. Potential electricity export for the RCL Plasma process (per ton of feedstock)

[Energy values are per ton of input feedstock]	Units	Energy at exit of gasifier per ton input	Electricity generation technology		
			Gas furnace and heat recovery boiler (20% conversion efficiency)	Reciprocating engine (35% conv. efficiency)	Gas turbine Combined Cycle (45% conv. efficiency)
Producer Gas Chemical Energy	mmBtu	9.50	1.90	3.32	4.27
Producer Gas Sensible Energy[a]	mmBtu	1.22	0.24	0.24	0.24
Sub Total	**mmBtu**	0.01	2.14	3.57	4.52
Less Electricity to power Torch	mmBtu		(2.09)	(2.09)	(2.09)
Electricity for Export	mmBtu		0.06	1.48	2.43
Electricity for Export	kWh		16	434	712
Net efficiency to electricity[b]	%		**0.5**	**14.3**	**23.5**
Power Export[c] - **100t/day** input	MWe		0.07	1.8	3.0
Power Export[c] - **500t/day** input	MWe		0.34	9	15

a. Assumes sensible energy is converted to electricity with 20% efficiency in each case.
b. Based on input energy of 4680 Btu per pound of MSW.
c. Assumes 24 hrs/day operation.

Emissions

There will be solid residue from a plasma arc conversion process, some of which may have a market. If no market is available (such as road bed aggregates) then the residue will probably be landfilled. The amount of solid residue, as discussed above, would vary from 5 percent to as much 30 percent (by weight) of the input stream. This depends completely on the characteristics of the feedstock (for example, the degree of sorting and separation of recyclables and mineral matter from the feed stream before thermal processing will effect solid residue amount). The volume of the solid residue will be relatively small, since it is denser than the average waste stream (the density is similar to that of glass).

Liquid residues (if any) depend on the product gas use which determines gas cleanup technology. Some gas scrubber systems can have liquid wastes that may require treatment before disposal. Water may condense from the product gas and be separated, but would likely not need treatment before disposal. Or, the water may have use on-site.

Air emissions from an RCL Plasma facility will also depend on how the product gas is used. If the gas is combusted for heat and electricity production, then air emissions types would be similar to those from liquid and gaseous fuel combustion systems. The amount of air emissions depends on the emission control technologies employed at the combustion and power generation stage.

The survey response from RCL claims that air emissions meet U.S. EPA and EU regulations and that the slag is ‘nonleachable’. However, no test reports of emissions were submitted.

The patent (Carter and Tsangaris, 1994) lists data from what appear to be extensive gas emissions and slag testing from operation of the research facility with flaring of the product gas (see Figure G-1).

Table G-5 displays the gaseous emissions data contained in the 1994 patent. The units are given in mass of emission per metric ton (1,000 kg) of refuse material processed. Gas was sampled at the outlet of the quencher and in the burner or flare exhaust (see Figure G-1). The degree of sorting of the MSW feedstock before input to the reactor was not described, but general process descriptions in the patent imply that minimal sorting occurred. Large metal, and perhaps glass, objects were probably removed to allow the waste to pass through the feed mechanism. It was assumed that all the chlorine containing compounds in unsorted MSW (PVC and much of the food waste which contains NaCl) were present, as well as many metals.

Table G-5. Gaseous emissions from plasma arc facility
(average of two lab-scale experiments, source; U.S. patent 5280757)

Emission (per 1000 kg of processed material)	Units	Quencher Outlet	Burner Exhaust	Reduction by Burner (%)
VOCs				
PCDD	(μg TEQ)	0.165	0	100
PCDF	(μg TEQ)	2.4	0.4	83.3
Chlorophenyls	(μg)	12350	ND	100
Chlorobenzenes	(μg)	4930	3940	20.1
PCB	(μg)	ND	ND	-
PAH	(mg)	107500	14650	86.4
Acid Gases				
Hydrogen Chloride	(g)	136	1.1	99.2
Hydrogen Fluoride	(g)	0.2	1.05	-425
Hydrogen Bromide	(g)	ND	ND	-
Selected Metals				
Antimony	(g)	1.5	0.065	95.7
Arsenic	(g)	0.4	0.055	86.3
Cadmium	(g)	0.4	0.055	86.3
Chromium	(g)	0.15	0.11	26.7
Copper	(g)	17.5	0.6	96.6
Lead	(g)	33.5	1.15	96.6
Mercury	(g)	0.0075	ND	100
Nickel	(g)	0.2	0.12	40

Table G-5 shows that VOCs in the burner exhaust are substantially reduced from the levels in the product gas. PCDF was emitted at 0.4 μg TEQ/1,000kg and PAH compounds were present in the amount of 14,650 mg/1,000 kg (Current U.S. MSW combustion emissions of TEQ are about 0.5 μg TEQ/1,000kg for plants with the 1995 MACT upgrades). No explanation was given for the increase seen in hydrogen fluoride in the burner exhaust.

The fate of the metals in the post-quench product gas is unclear since burning the product gas would not destroy metals. Perhaps the metals oxidized and coalesced to particulate matter and were not measured. Possibly, the quenched gas sampling location was intermediate in the quenching process so that metal vapors were measured in the gas prior to condensing in the remaining quenching operation. A more complete description of the testing methods would be needed than that discussed in the patent in order to reliably determine the fate of heavy metals.

Table G-6 shows the results of digesting the slag in an aqua regia solution of hydrochloric and nitric acid that dissolved about half the mass of the slag. The soluble and insoluble components of the metals are shown. This amount of dissolution is much more extreme than would be encountered in a landfill (because of the strong acid aqua regia solution).

Table G-6. Metals Content in the Soluble and Insoluble Fractions after Dissolving about Half the Mass of the Slag in an Aqua Regia Solution of Hydrochloric and Nitric Acid

	Metals* in Slag (μ g/g)		
	Soluble	Insoluble	Total
Aluminum	94500	1605	96105
Antimony	7.5	2.11	9.61
Arsenic	2	0.185	2.185
Barium	1830	27	1857
Beryllium	1	-	1
Bismuth	ND	-	ND
Boron	205	-	205
Cadmium	0.5	ND	0.5
Calcium	105000	714	105714
Chromium	285	9.7	294.7
Cobalt	13.75	0.34	14.09
Copper	810	30	840
Iron	37500	714	38214
Lead	118.5	-	118.5
Lithium	38.5	-	38.5
Magnesium	22000	183	22183
Manganese	1455	50.35	1505.35
Mercury	0.29	ND	0.29
Molybdenum	2.5	ND	2.5
Nickel	44	ND	44
Phosphorus	4250	-	4250
Potassium	14100	269.5	14369.5
Selenium	ND	ND	ND
Silicon	580	228926.5	229506.5
Silver	ND	ND	ND
Sodium	40000	485.5	40485.5
Strontium	300	ND	300
Tellurium	ND	ND	ND
Tin	24	ND	ND
Titanium	5650	820.5	6470.5
Vanadium	39.5	1.54	41.04
Zinc	365	6.5	371.5
Total* (μ g/g of slag)	329122	233846	562968
Total* (mass %)	32.9	23.4	56.30
Slag Partitioning (%)	48	52	100
Metals Partitioning (%)	58	42	100
Slag Metals per tonne of refuse (kg/1000 kg)			61890
Slag Metals per Input Metals (%)			97

*Mass of elemental metal (not oxide form) in slag

Hitachi Metals (Japan)

Plasma Arc Gasification/melting of MSW (commercial/commercial scale demonstration).

After demonstration of the gasification technology for MSW at the pilot plant in Yoshii, Japan during 1999–2000, the Japanese government certified the technology for construction of a commercial size plant. The system uses the Westinghouse plasma melting reactor. It is an air-blown gasifier with plasma heat to assist in complete oxidation of the fixed carbon and slagging of the inorganic residue. The hot synthesis gas is combusted in a burner immediately downstream of the gasifier reactor (see Figure G-3). The hot combustion product gas can be used in a heat recovery boiler for process steam or to power a steam turbine for power generation.

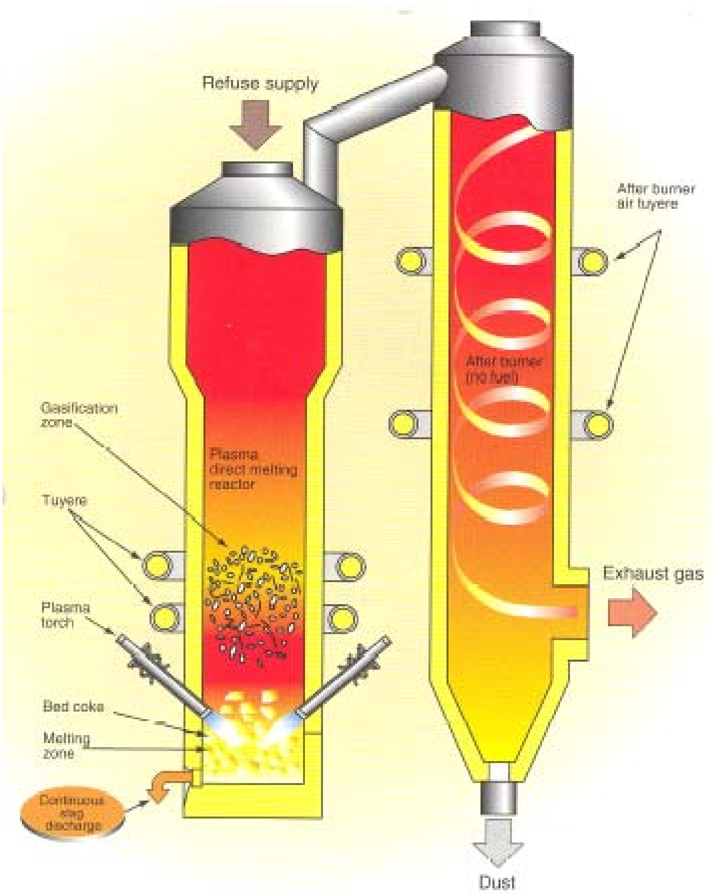


Figure G-3 Schematic of Hitachi Metals plasma assisted gasifier and gas burner (Source; Hitachi Metals)

Below are the Hitachi Metals plasma systems in operation:

> Yoshii Plant. Plasma processing of MSW; prototype plant commissioned in 1999; processes 26.4 tons per day; syngas used to provide hot water to adjacent recreational facilities.

Mihama-Mikata Plant. Plasma processing of MSW (19 tons per day) and sewage sludge (5.3 tons per day); commissioned in 2002; syngas used to provide hot water supply for plant operations and adjacent recycling center.

Utashinai Plant. Plasma processing of MSW and ASR; commissioned in April, 2003; processes 200 tons per day (capacity is 300 tpd if 100% MSW); syngas used to produce electricity with a steam turbine. Gross electricity generated is 7.9 MW, with 4.3 MW sold to local power company (46% parasitic load- plasma torches and other facility loads).

Table G-7 shows limited stack emissions data for the Utashinai Plant. Table G-8 shows results from slag leachate testing from the same plant (as reported by Westinghouse Plasma).

Table G-7 Limited stack gas emissions from Hitachi Utashinai Plant (provided by Westinghouse Plasma)

	Units	Measured value
PM	g/Nm^3	<0.01
NOX*	ppm	83
HCL	ppm	7
Dioxins/Furans	$ng\text{-}TEQ/Nm^3$	<0.01
Tar		non detect

Table G-8 Results from slag leachate testing for the Hitachi Utashinai Plant (provided by Westinghouse Plasma)

	Symbol	Unit	Regulation	Measured value
Cadmium	Cd	mg/liter	<0.01	<0.001
Lead	Pb	mg/liter	<0.01	<0.005
Arsenic	As	mg/liter	<0.01	<0.005
Hexavalent Chrome	Cr+6	mg/liter	<0.05	<0.02
Total Mercury	T-Hg	mg/liter	<0.0005	<0.0005
Selenium	Se	mg/liter	<0.01	<0.005
Dioxin	DXN	ng-TEQ/g		6.5E-07

Solena Group (Washington, DC)

The Solena Group has developed an integrated plasma gasification and combined cycle (IPGCC) plant that process municipal solid waste, industrial, toxic, hospital and other wastes, including tires and plastics. The IPGCC process uses a high temperature plasma torch to dissociate wastes into a synthesis gas, which is used to power a gas turbine and combined cycle steam turbine. No IPGCC systems have been built. The company or current members have been involved in a wide variety of projects and ventures that utilize plasma arc technology. Most of the applications were related to hazardous or low-level nuclear waste volume reduction or in metals production. There have been some test programs on MSW or generic waste disposal but details were not provided. The company is involved in attempts to locate pilot scale facilities in the Caribbean to help serve the cruise line industry with potential shipboard waste disposal systems. The company is involved in development projects in Spain, France, the UK, the U.S., and Malaysia.

The Solena PGV Reactor employs plasma torches to heat the reactor to 7,200–9,000º F at atmospheric pressure. At this operating temperature, the PGV process uses a carbon-based catalyst and oxygen-enriched air to cause the hydrocarbon or organic material to undergo partial oxidation creating a gas mixture containing primarily H2 and CO. CO2 and N2 are also present, depending on the amount of air enriched oxygen used.

The syngas has a heating value varying from 150 to 300 BTU/scf, which is about 1/6 to 1/3 of that for natural gas. The Solena process requires an air separation plant for oxygen-enriched air for the gasifier. Supplying oxygen to the reaction allows internal heat generation, which reduces required torch power (compared to plasma torch systems heating a pyrolysis reaction), but also reduces the chemical energy content of the produced gas (because it's been partially oxidized).

Minimal detail regarding energy and material balance or feedstock characteristics were provided. The Solena survey response did indicate "overall efficiency of electricity production is about 35%." A 20-ton per hour unit would have a net power output of 50 MW (60 MW gross).[**] From this information, the energy in the fuel is calculated to be about 14,600 Btu/lb (34 MJ/kg), which is equivalent to that of mixed plastics. All else being equal, a Solena facility utilizing raw post-MRF MSW would require some 62 TPHof feedstock to produce 50 MW.

Georgia Tech Research Institute (Atlanta, Georgia)

Georgia Tech Research Institute is part of an eight-member consortium (Geoplasma, LLC) that responded to a City and County of Honolulu RFP for an MSW plasma or gasification conversion system. The proposed facility is a 100,000 TPY (376 TPD) plasma arc waste treatment plant. The technology is the Westinghouse Plasma Corporation "Plasma Direct Melting Reactor" (PDMR) and is essentially the same systems in use by Hitachi Metals in Japan.

PDMR technology is claimed to treat all solid and liquid organic and inorganic materials. Georgia Tech reports that "typical" feedstocks entering this kind of facility are 60% MSW. 25% ASR, and 15% "recycling residuals." Preprocessing of the MSW feedstock is not necessary but is proposed for the Honolulu facility. Additional inputs to the facility include electricity, coke, and limestone (amounts proprietary).

The Honolulu facility is estimated to produce 10.6 MW of which 4.1 MW will be consumed by plasma torches and other facility loads (39% parasitic load), and 6.5 MWe will be sold to the Hawaiian Electric Company (HECO) under a negotiated PPA agreement. The net available power amounts to only 415 kWh per input ton, which is less than the existing H-Power combustion facility (540–640 kWh/ton).[296] The syngas (H_2 and CO) could also be used directly as a heating fuel, for H_2 extraction for use with fuel cells, or to produce liquid fuels such as methanol.

Georgia Tech also cites the operating plants in Japan and the Hitachi Metals emissions information for reference.

[**] Solena's "white paper" on IPGCC states that the process is about 5% more efficient than coal-fired power plants (http://www.solenagroup.com/html/images/fuelflexible.pdf)

Westinghouse Plasma Corporation (Madison, PA)

Westinghouse Plasma manufactures and supplies plasma torches to the industry. The company also has developed a plasma-enhanced gasifier for waste materials (low grade coal, petcoke, MSW, and other industrial wastes). Companies marketing systems that specify the Westinghouse reactor include, Geoplasma LLC, Recovered Energy Inc, and Hitachi Metals.

The reactor is an atmospheric air or oxygen-blown gasifier with plasma torches projecting into the lower portion of the vessel. The plasma torches heat the inorganic residue (with air/oxygen injection) and gasify or combust the fixed carbon that has reached the bottom of the reactor. Above the plasma melting zone are two levels of air injection, which allow for partial oxidation of the feed material as in standard gasification (see Figure G-4). The reactor is fuel-flexible and is based on a blast-furnace design. Westinghouse reports that for 15.4 tph of coal feedstock, the plasma torches require 2.4 MW of power and the reactor will use 64.6 tph of air (air:fuel ratio of 4.2).[297]

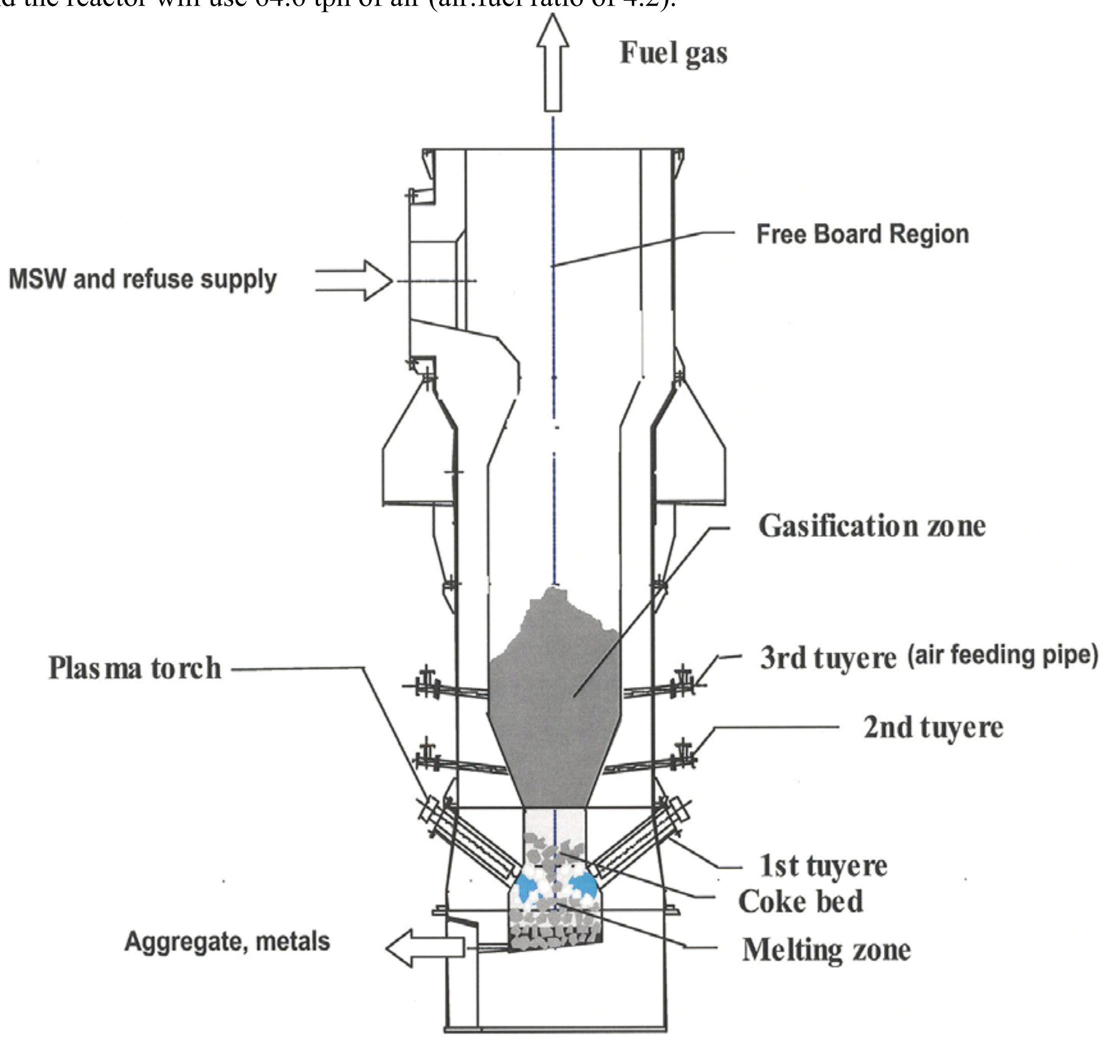


Fig. G-4 Conceptual Cross-Section of Westinghouse Plasma Corporation Plasma Direct Melting Reactor (tuyere is blast furnace terminology for air injection port)

Recovered Energy, Inc. (Pocatello, Idaho)

Recovered Energy, Inc. (REI) describes the status of their technology as commercial (though they haven't sold any plants for MSW). REI does not hold any patents but would instead use components and processes for the plant under license from other companies. The company currently does not operate any other units but cites the three Hitachi plants in Japan for reference (as do several other vendors) REI would use a Westinghouse plasma melting furnace and a gas turbine combined cycle for power generation.

The REI process accepts any feedstock that is not radioactive, and technically the plant can process hazardous waste with the same equipment. However, regulatory requirements may not allow the same plant to process hazardous waste. No preprocess shredding is required for anything under 3 ft in diameter. Truck tires would be cut in half, and car tires can go in whole. Feedstock moisture content doesn't matter for technical purposes, but for financial purposes the REI process would like as little water as possible (for example, sewage sludge would be dewatered to 25% moisture).

Optimal plant size is 3,000 TPD of MSW. Marketable products from the process are electricity, HCL (up to 20% concentration), sulfur (fertilizer grade), sodium hydrosulfide (whitener for the paper industry), recycled metal, vitrified glass (uses range from road base and aggregate material to blocks to ceramic type materials), and ethanol. In addition, waste heat can be used to distill water or for desalinization. A MRF is unnecessary, but developers would pursue one if required in order to permit the facility .

Material and energy inputs for the system include a small amount of makeup water for cooling (most of the cooling comes from an air-cooled condenser), and natural gas to start up the gas turbine and supplement any turbine capacity not supplied by the syngas. Electricity needs are supplied internally, although the plant may be configured to sell all the power to the grid and then buy back what is needed internally for operations. All steam requirements are supplied internally.

Table G-9 shows a basic material balance reported by REI. Air comprises the majority of the input mass. The air-to-fuel ratio is 1.4 (mass of air per mass of fuel). Table G-10 displays expected synthesis gas composition reported by REI.

Table G-9 Material balance reported by REI

Component	Flow rate (tons per day)	Fraction of total input or output (%)
Inputs		
MSW	2988	38
Silica for flux	130	1.7
Coke	166	2.1
Air	4500	57.8
Outputs		
Glass	590	7.6
Metal	234	3
Synthesis gas	6960	89.4

An energy balance was difficult to derive from the given data. REI reports that the net electricity production (from a 3,000 TPD plant) is about 100 MW based on a 29% overall conversion efficiency and a MSW HHV of 4800 Btu/lb (11.2 MJ/kg). Any turbine capacity not fired with syngas will be fired with natural gas. Mass reduction efficiency is reported as 99.9 percent conversion to usable products, and the carbon conversion efficiency is reported as >99 percent (small amount of carbon being present in the glass).

Table G-10 Synthesis gas composition reported by REI

Component	Concentration (% volume)
CO	24.0
CO_2	2.1
H_2	10.1
H_2O	20.1
N_2	42.2
C_2H_4	1.2
H_2S, HCl, PM, metals	0.3

REI does not have actual reports of gaseous emissions. The company cites statistics of the Hitachi plants in Japan as reported to them by Westinghouse Plasma. REI is in the process of filing for permits on several plants but cannot divulge the information at this time.

Integrated Environmental Technology (Richland, Washington)

Integrated Environmental Technology IET was formed in 1995 as a spinoff company from Battelle Pacific Northwest National Laboratory. Integrated Environmental Technologies has developed a steam reforming gasification technology based on plasma technology. The process is called a Plasma Enhanced Melter and utilizes a plasma arc at just below atmospheric pressure to produce a synthesis gas.

The synthesis gas can be used for power generation or for the production of other chemicals including hydrogen, carbon monoxide, and methanol. Simultaneously, the inorganic components are melted and incorporated into a vitrified (glassy) product. Currently, IET has built three prototypes and four commercial units. They are located in Richland, Washington; Oahu, Hawaii, Okinawa, and Kyushu, Japan. A small test facility is located in Richland. The four commercial units include one for nuclear waste, one for industrial waste, and two for medical waste. IET is also discussing projects with a Japanese partner for MSW, but has no plants currently built. The PEM system was also evaluated by the Environmental Technology Evaluation Center (EvTEC) in an extensive test program in the spring of 2000.

PEAT (Northbrook, Illinois)

PEAT (Plasma Energy Applied Technology, Inc.) has developed a plasma process that can be used for the conversion of waste. The plasma pyrolysis converts the feedstock to a syngas that is subsequently sent through a turbine to produce electricity. The producer gas can also be used to make methane, methanol, and plastics. PEAT has several plants in operation in the U.S. and abroad including a 10 TPD facility operating on hazardous wastes and organic sovents in Taiwan; another 3TPD is also being built there. The smaller unit in Taiwan would be a pilot plant to use for testing with a large range of waste types, but it is intended primarily for vitrifying waste combustion ash. A 6-10 TPD unit has been operating in Virginia since 1999 processing medical waste for the U.S. Army.

Phoenix Solutions (Crystal, Minnesota)

Phoenix Solutions has developed a technology that converts organic waste to syngas (H_2 and CO) in a furnace using an electric plasma arc. The system produces a pyrolysis gas containing approximately 45% by volume hydrogen gas and 45% by volume carbon monoxide. The process uses steam as the primary medium for carbon gasification. Air is used as the plasma gas medium; however, natural gas can also be used, providing greater flexibility and yield.
The plasma arc torches within the furnace have the capability to produce temperatures that range from 7,200–12,400^{o} F [4,000–7,000^{o} C] allowing complete dissociation of the feedstock without the production

of tars and partially disassociated hydrocarbons. Inorganic material in the waste stream is melted into a slag and removed from the furnace. The pyrolysis gas is also low in nitrogen and carbon dioxide. The cost of the gas is estimated to be $3.63/MM BTU if the tipping fee is $37/ton.

The technology can also be coupled with a combined cycle gas turbine to provide electricity. The Phoenix system purportedly is capable of higher operating temperatures without the formation of tars, and there is no requirement for combustion air in the processing vessel. Other downstream subsystems are smaller and less expensive than traditional gasification systems. Vapor conditioning and gas cleanup is also simplified due to the absence of tars, nitrogen, and carbon dioxide in the pyrolysis gas. The Phoenix system has been operated on hazardous waste, medical waste, and PCBs. However, it has not been operated on municipal solid waste. A conceptual design has been developed to accept MSW without preprocessing. Thirty-three commercial waste destruction systems are currently operating in the field.

Hawkins Industries (Indiana, Illinois)

Hawkins Industries has a plasma pyrolysis process that has been developed for them by PEAT. They are planning to implement the technology at a site in Indianapolis. The unit will be co-located on the site of a materials recovery facility. The unit will be designed primarily for the processing of higher-priced feedstocks such as medical waste. The company has also proposed to put a facility in a Kaiser medical facility in San Diego, California.

Appendix H
Descriptions of Biochemical Processes

Biochemical Process Current Status and Survey Results

Table H1. Companies and/processes currently operating facilities (or attempting commercialization) using biochemical processes to convert biomass components of MSW

Company Name	Corp. Headquarters	Process Name	Process Type
Valorga	Montpellier, France	Valorga	Anaerobic digestion (OS – HS)
Wehrle Werk AG	Emmendingen, Germany	Biopercolat	Anaerobic digestion (MS-HS)
Wright Environmental Management	Ontario, Canada		In vessel composting
CiTec	Finland/Sweden	Waasa	Anaerobic digestion (OS – LS)
Linde-KCA-Dresden	Dresden, Germany		Anaerobic digestion & composting (MBT)
Kompogas	Glattbrugg, Switzerland	Kompogas	Anaerobic digestion (OS – HS)
U-plus Umweltservice	Ettlingen, Germany	ISKA	MBT followed by anaerobic digestion
Eco Tec	Finland	WABIO	Anaerobic digestion (OS – LS)
Organic Waste Systems	Gent, Belgium	Dranco	Anaerobic digestion (OS – HS)
BTA (Canada Composting in North America)	Munich, Germany (Ontario, Canada)	BTA	Anaerobic digestion (OS or MS – LS)
Arrow Ecology	Haifa, Israel	Arrow Bio	Anaerobic digestion (MS – HS/LS)
Onsite Power Systems	Camarillo, CA	APS (UC Davis)	Anaerobic digestion (MS- HS/LS)
Masada Resource Group	Birmingham, AL	CES Oxynol	Acid hydrolysis for ethanol production
BRI	Fayetteville, AR		Gasification w/ fermentation to ethanol
Arkenol			Acid hydrolysis for ethanol production
WTE (w/ Genahol)l	Santa Maria, CA	Genahol/ BEI	Hydrothermal and acid hydrolysis for ethanol production

OS= One Stage
MS = Multi Stage
MBT= Mechanical-Biological Treatment
HS = High Solids
LS= Low Solids

Fermentation to Ethanol Status

Masada OxyNol (Birmingham, Alabama)

The Masada OxyNol process converts biomass components of MSW into ethanol and other by-products. These by-products include carbon dioxide, lignin, gypsum, fly ash and all recyclable materials (glass, plastics, ferrous and non-ferrous metals). Key components or steps in the process include:

- MRF.
- Feedstock preparation (shredding and drying).
- Acid hydrolysis unit.
- Fermentation and distillation units.

The MSW delivered to the facility is sorted manually and mechanically; all recyclable materials are recovered and inert materials removed. The remaining fraction of the waste stream is shredded and dried. Wastewater biosolids can also be processed in a separate, parallel process train.

Figure H-1 shows a schematic of unit operations for the Masada process. Concentrated sulfuric acid is used to hydrolyze the feedstock. The lignin and other solid residues can be used as a renewable boiler fuel to help meet internal steam demands which include the steam heat used in drying the feedstock (natural gas is used to produce steam as well). The sulfuric acid is recovered and recycled. The sugar stream is then treated with lime to remove heavy metals and undergoes a concentration step and pH adjustment prior to fermentation and distillation into alcohol. The metals precipitate out of the solution as a crystalline synthetic gypsum. Fermentation of the sugar stream is accomplished using commonly available yeast and yields recoverable carbon dioxide in addition to ethanol.

The technology is currently precommercial, with construction of the first commercial facility anticipated to start in 2004 at Middletown, New York. This facility has been permitted for 230,000 TPY of MSW and 71,000 TPY of bone dry biosolids. Based on the Middletown waste volume and characteristics, Masada estimates this facility's ethanol production will be 8.5 million gallons per year (37 gallons EtOH per ton or presorted MSW).[††] Ten percent of the material (by weight) coming into the process is inert and/or non-recyclable and will need to be landfilled. Table H-2 lists U.S. patents associated with the Masada Oxynol process (all are assigned to Controlled Environmental Systems Corporation of Birmingham, Alabama). Several have identical titles and abstracts; actual differences and advancements require a close reading of the patents.

[††] Based on the permitted 230,000 TPY permitted waste capacity.

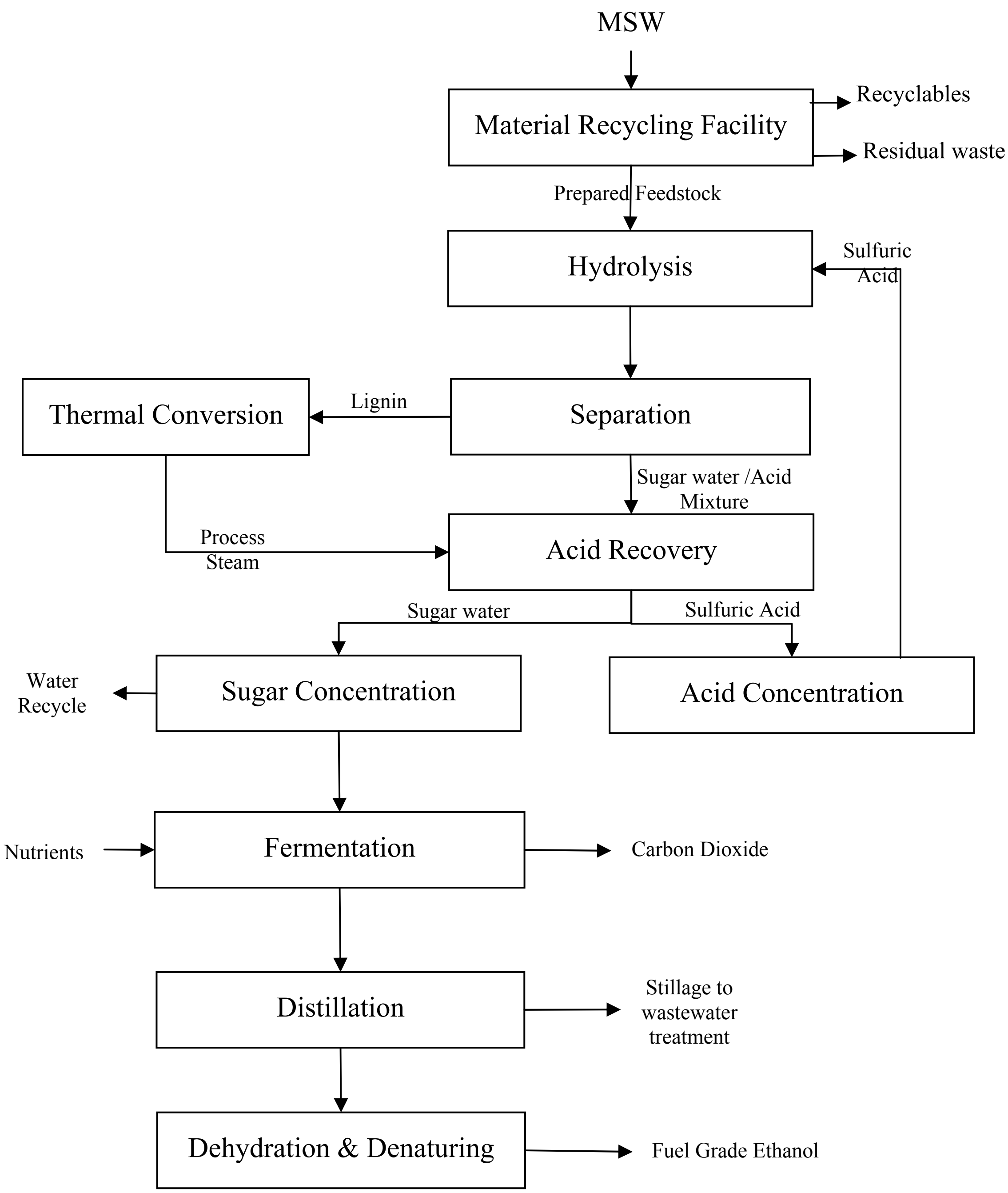


Fig. H-1 Masada Oxynol Process Flow Diagram (Masada Resource Group)

The Middletown facility has been issued all necessary environmental permits including a Part 360 Solid Waste Management Facility permit from the New York State Department of Environmental Conservation, which administers a Federal Title V Air Permit from the U.S. EPA. The facility is being financed through a combination of private equity and local revenue bonds.

Table H2. List of U.S. Patents Associated with the Masada Oxynol Process

Patent Number	Year	Title
5407817	1995	Municipal solid waste processing facility and commercial ethanol production process
5506123	1996	Municipal solid waste processing facility and commercial lactic acid production process
5571703	1996	Municipal solid waste processing facility and commercial ethanol production process
5779164	1998	Municipal solid waste processing facility and commercial ethanol production process
5968362	1999	Method for the separation of acid from sugars
5975439	1999	Municipal solid waste processing facility and commercial ethanol production process
6267309	2001	Municipal solid waste processing facility and commercial ethanol production process
6391204	2002	Method for the separation of acid from sugars
6419828	2002	Method for the separation of acid from sugars

Mass and Energy

The typical facility will import electricity since the primary product is ethanol (though some or all of the required heat and electricity can be produced from the lignin fraction). The process heat requirement (e.g., drying, distillation,e tc.) may be a better use for the lignin. Some water will be required for the Masada process. The scenario being analyzed for the life cycle analysis study (RTI/NREL) assumes the process converts 34 TPH of sorted MSW producing 940 gallons per hour of ethanol. In the RTI scenario, the lignin fraction is used to supply all internal heat and power needs with a 4.5 MWe surplus for export. If, as in Middletown, New York, a facility is located near a wastewater treatment facility, it can utilize raw or partially treated waste water for some of its process water requirements. See Figure H-2 and Table H-3 for material balances for two feedstock scenarios (one using sorted MSW and WWT biosolids and the other using a sorted MSW feed stream).

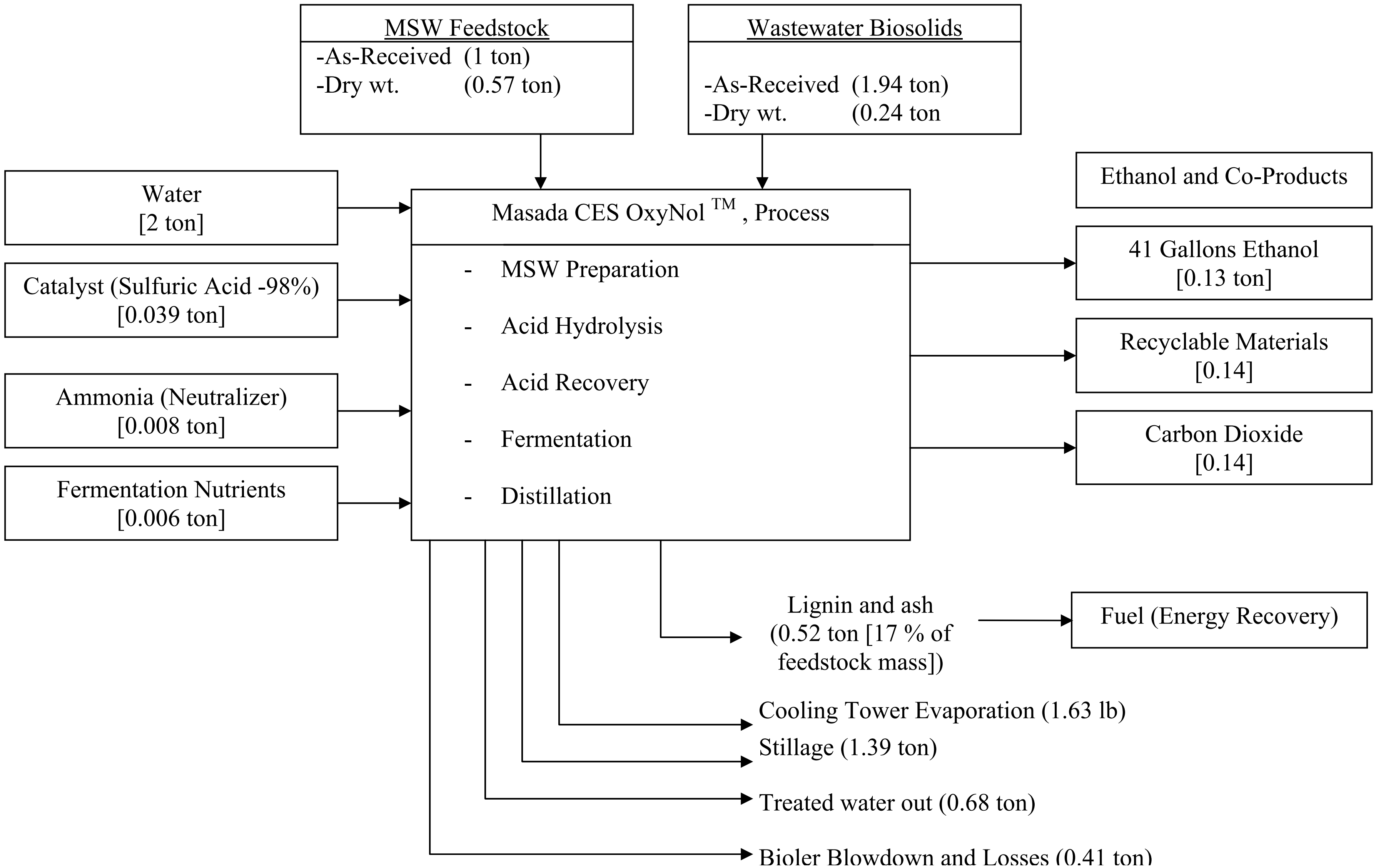


Fig. H-2. Masada Process Material Balance for 1 ton MSW and 1.94 ton Biosolids Input

These scenarios (Table H-3) show amounts of product and input streams per ton of sorted MSW. Notable is the large amount of water required for the process (The reason for the large difference in required water between the two scenarios is unclear. One would expect the biosolids/MSW scenario to require less water because of water brought in with the biosolids).

Masada indicates that "the majority revenue stream for a typical OxyNol facility comes from waste not products produced from waste." Reliance on stable tipping fees for economic viability of this type of facility seems characteristic.

Table H-3. Mass Balance for Masada Process (2 Scenarios)

	MSW + WWT Biosolids[a]		MSW only[b]	
Inputs	(Tons)	(% of total)	(Tons)	(% of total)
MSW	1.00	19.9	1	44.0
Biosolids	1.94	38.6		
Water	2.04	40.5	1.20	52.6
Sulfuric Acid	0.039	0.8	0.06	2.6
Lime/wwt chems			0.02	0.7
Nutrients	0.006	0.1	0.0009	0.04
ammonia	0.008	0.2	0.0006	0.03
Totals	5.04	100	2.27	100
Outputs				
Lignin /ash (dry)	0.52	10.3	0.11	4.7
Stillage	1.39	27.6		
Treated Water	0.68	13.5	0.61	27.1
Boiler and cooling water blowdown and lignin moisture	2.04	40.4	1.21	53.3
Ethanol	0.13	2.6	0.09	4.0
CO2	0.14	2.7	0.08	3.6
Gypsum	-	-	0.02	1.0
Recyclables	0.14	2.8	0.14	6.2
Totals	5.04	100	2.27	100
Ethanol production (gallons per ton of wet Feedstock)[c]	14		28	
Net Water requirements (gallons per ton wet feedstock)	326		139	

a). Data provided by Masada.
b). Data provided by RTI/NREL.
Note that one scenario uses large amount (2:1 by mass compared to MSW) of high moisture biosolids (87% moisture).

Arkenol (Mission Viejo, California)

Areknol develops cellulosic ethanol production facilities that use concentrated acid hydrolysis. The company has operated various pilot scale facilities and has designed and built a facility in Japan that is currently operating using urban wood as feedstock. Ethanol production is currently viewed as the primary product from cellulose hydrolysis and fermentation (due to expected market in California for ethanol).

However, a wide range of intermediate chemicals and end products can be produced from hydrolysis and fermentation or other chemical conversion of biomass feedstocks (See Figure H-3). Biobased products and markets are expected to develop as conversion costs and efficiencies decline (and/or as petroleum costs rise).

For MSW, the preferred feedstock is the cellulosic and other biomass components of MSW. Arkenol assumes that those materials within the feedstock stream that have market value as recycled material are first removed from the stream.

Feedstock preparation requires shredding the material to ¾" minus using standard industry equipment (for example, tub grinder) and drying to about 10% total moisture using low value heat energy that is recovered and recycled from the process. While the 10% moisture is preferred, moisture can range up to 30% for short periods of time without causing upset.

The concentrated acid hydrolysis route to the production of fermentable sugars is remarkably tolerant of changes in feedstock composition. This is an advantage because it increases the range of acceptable feedstocks. Opportunistic or co-feedstocks can be therefore be utilized.

The following comparisons between the Arkenol and the Masada processes were made by the authors of the RTI/NREL LCA study:

Number of hydrolysis stages—Masada has a single hydrolysis step, while Arkenol has two hydrolysis stages.
Focus on MSW—Masada has developed their technology specifically for MSW; Arkenol has a more general feedstock emphasis.
Sugar concentrating step—Masada has a sugar concentrating step using reverse osmosis prior to fermentation, and Arkenol does not.
Acid/sugar separation step—Arkenol uses a strongly acidic ion exchange column that retains the sugar and elutes the acid. Masada uses an exchange column with the reverse, which provides an acid stream with a higher concentration.
Acid recycle scheme—also differs

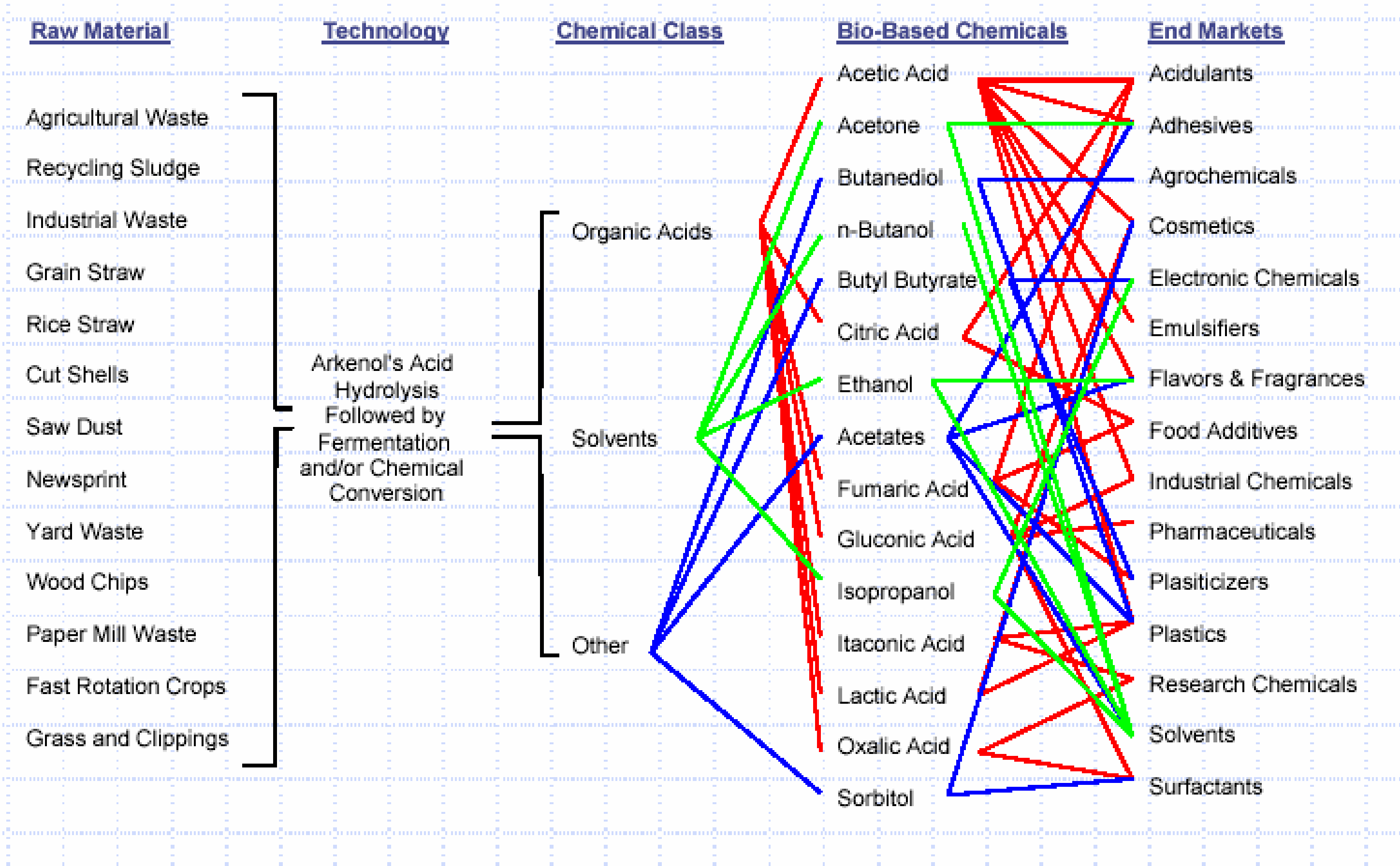


Fig. H-3. Relationship between Biomass, biobased Chemicals, and End Markets (Adapted from Arkenol Survey Response)

Simple (and partial) mass and energy inputs for what Arkenol reported for a typical ethanol from cellulosic feedstock using concentrated acid hydrolysis is displayed in Table H-4. The mass balance does not close completely, and no conversion of the lignin residue for energy was indicated. The masses are based on feedstock dry weight, so the ethanol production quantities cannot be directly compared to Masada's process. Adjustment to comparable feedstock moisture basis would be needed before directly comparing ethanol production.

Table H-4. Partial Mass and Energy Balance for the Arkenol Process

Inputs	lb/hr	(Tons)
Cellulose Feedstock (Dry)	32480	1
Water	1767	0.05
Conc. Acid	1028	0.03
Lime	507	0.02
Nutrients	209	0.006
Totals	35991	1.11

	(MMBTU/hr)
Natural Gas used	8257
	(MWh)
Electricity used	1.36

Outputs	lb/hr	(Tons)
Lignin Cake	18387	0.57
Gypsum Cake	2475	0.08
Sewer	-	
Landfill	-	
Protein Crème	443.5294	0.01
Fuel Ethanol	7085	0.22
CO_2	2104	0.06
Totals	30495	1
% Unaccounted	9.9	
Gallons Ethanol per dry ton of feed		67

Waste to Energy (WTE) (Santa Maria, California)

WTE responded to the survey but did not want any of the survey information disseminated to the public. The information developed here is exclusively from literature and Internet sources.

WTE is working with Genahol Corp. to install a commercial validation plant for ethanol production in Santa Maria, California. The project would use post-MRF biomass material for ethanol production and then pyrolyze the residual lignin and plastics for process electricity. Genahol is developing a hydrothermal and mild acid hydrolysis, followed by fermentation-to-ethanol process (the Brelsford Engineering, Inc. Process; see Figure H-4).

The project reportedly will also use a pyrolysis with catalyst procedure to convert plastic from the MRF to a liquid fuel to provide power for the ethanol production facility. UNCI Engineering and Merrick and Company, Aurora, Colorado, will probably develop the pyrolyzer.

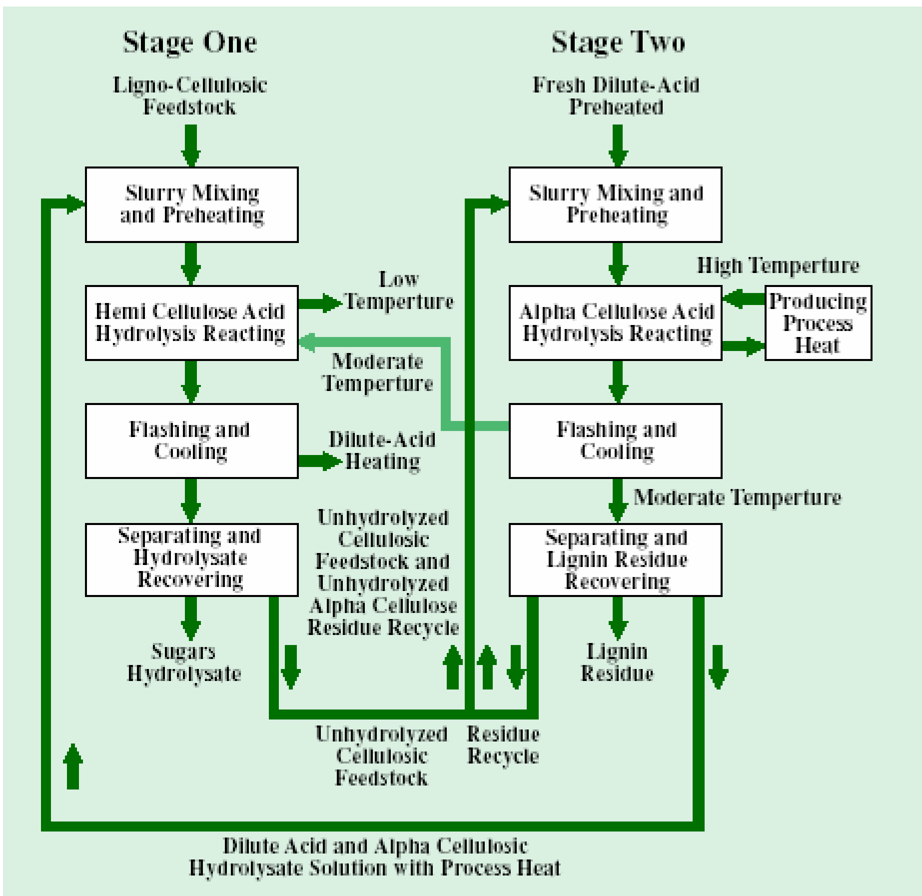


Fig. H-4 BEI/Genahol Hydrolysis and Ethanol Process Schematic
Adapted from BEI Project Fact Sheet (DOE Energy Efficiency and Renewable Energy)
http://www.eere.energy.gov/inventions/pdfs/bei.pdf

Anaerobic Digestion Current Status

Arrow Ecology Ltd. (ArrowBio process) (Haifa, Israel)

The ArrowBio process is an anaerobic digestion conversion process designed to accept the full unsorted MSW stream. Inherent in the process is a fully integrated water-vat sorting and cleaning facility, which yields sorted recyclables much like a typical MRF (the exception being that all biomass components, including paper and cardboard, are eventually carried into the low solids biochemical treatment system). If paper recovery is desired, paper must be separated upstream of the water-vat stage. The sorting process also separates most of the non-recyclable inert material from the biodegradable matter.

The biochemical processing concept employed is unique to MSW anaerobic digestion systems in that it utilizes "up-flow anaerobic sludge blanket" (UASB) technology commonly used by wastewater treatment plants. The company has experience with designing and building wastewater treatment facilities.

The process outputs are sorted into the following categories: ferrous and non-ferrous metals, glass and other mineral matter, plastics, biogas, nondigestible residue, and "low-strength" (low chemical oxygen demand [COD] or biochemical oxygen demand [BOD]) wastewater. The biogas can be burned in gas engines on-site for heat and power or upgraded to pipeline quality gas, or processed to a liquid natural gas-like compound for use as transportation fuel. The emissions from the biogas utilization, therefore, depend on the end use of the gas, but would be similar to those from existing biogas and natural gas applications. The low-grade wastewater can be used for irrigation (as is done at the facility in Israel for the on-site landscaping), or it can be treated in the local municipal wastewater treatment plant.

ArrowBio provided much information in the survey response, but many of the claims are difficult to corroborate since no independent review, data, or test results were made available. Arrow Ecology built and operates a 70,000 TPY commercial scale facility using the ArrowBio process. The facility is collocated with the Tel Aviv transfer station which currently handles approximately 1 million TPY for transport to a distant landfill. Arrow Ecology indicates that a 220 TPD facility (60,000–70,000 TPY depending on number of operating days) requires approximately 3 acres.

Currently the operating plant in Israel receives $24.50 per ton of material processed, and a new "landfill tax" will bring this tipping fee to $33.30 per ton. The facility was financed with company funds and a bank loan. Additional information made available by the company[298] gives estimated capital costs (for a U.S. installation) of US$12 million for a 220 TPD plant. The required break-even tipping fee is approximately $50 per ton. Reported product types and value for the Tel Aviv facility are listed below:

Product ◊	$/unit
Electricity	$50/MWh ($.05/kWh).
Plastic	$72/ton.
Metal	$63.5/ton.
Glass	Given away.
Organic soil amendment	Given away.
Liquid water	Used internally as makeup process water, with the excess used for landscape maintenance.

◊ Quantities of these products and Tel Aviv waste characterization were not reported‡‡.

Arrow Ecology holds U.S. patent 6,368,500 (Asa et al., April 9, 2002) for a waste treatment system. Though elaborate, the process utilizes a clever water-vat primary separator creating three material feeds: 1) the heavier material (sinkers), mostly non-biodegradable material composed of metals, glass, plastic with specific gravity (SG) >1, mineral matter, etc., 2) the lighter material (floaters), composed of floating plastics, containers, woody biomass, some food items, etc., and 3) the neutrally buoyant material, which is much of the biomass.

The floating material is skimmed off the water pit and reunited with the heavy "sinkers" fraction that is dredged from the bottom of the water pit. This stream passes through standard MRF-type separation and sorting mechanisms (See Figure H-5).

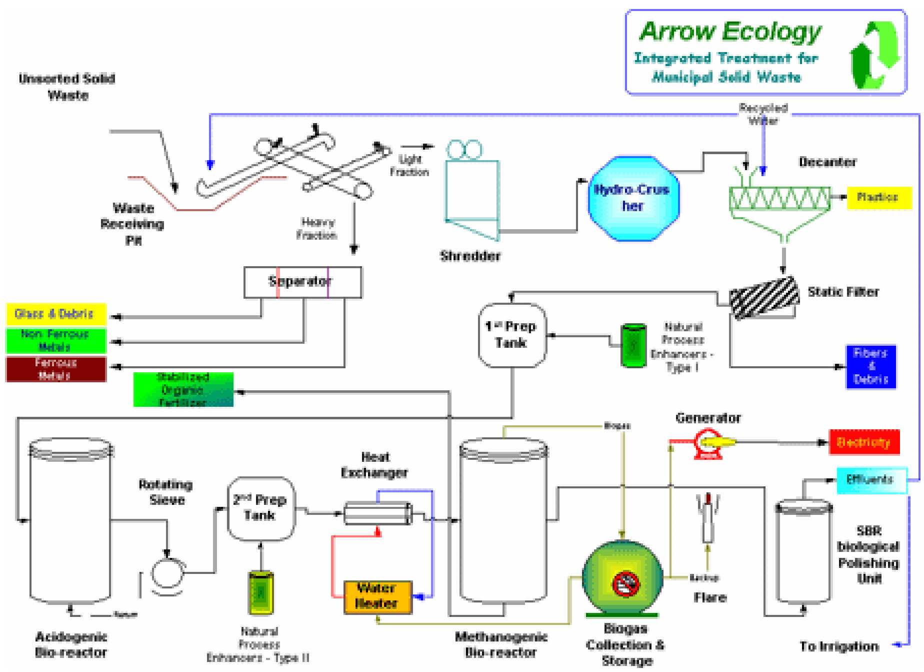


Fig. H-5. Schematic of the ArrowBio Process[299]

Soluble biomass begins to dissolve with agitation in the water vat. Dissolved and waterlogged/soggy biomass is carried out of the vat with liquid flow. Particle size reduction and dissolution of biodegradables continues with downstream travel. Size reduction is aided by passage through a slow-speed rotary shear, followed by a special Hydro-Crusher device (which is an aspect of the patent). Those particles still too large are returned to the vat through selective screening for repeat passage.

The biomass material received in various solid forms (food preparation and plate waste from homes and restaurants, food-tainted paper, vegetative trash, yard waste not diverted for composting, etc.) is transformed into a strong wastewater. As such, it is possible to apply low solids UASB wastewater treatment technology to the biodegradable fraction of MSW.

‡‡ The company website indicates the facility is expected to export 2-3MWe once in full operation. <http://www.arrowecology.com/mainpage/index2.htm>

Biological processing

The prepared biomass-rich watery solution flows from the water-vat separator to acidogenic bioreactors (anaerobic), where intermediated organic acids are formed. Effluent from the acetogenic reactor is screened and the large particles are returned to this first reactor. The liquid with smaller particles is heated to about 40º C before entering the UASB reactor, where the methane is produced (see Figure H-6). Presumably, the UASB reactor operates in the mesophilic temperature range.

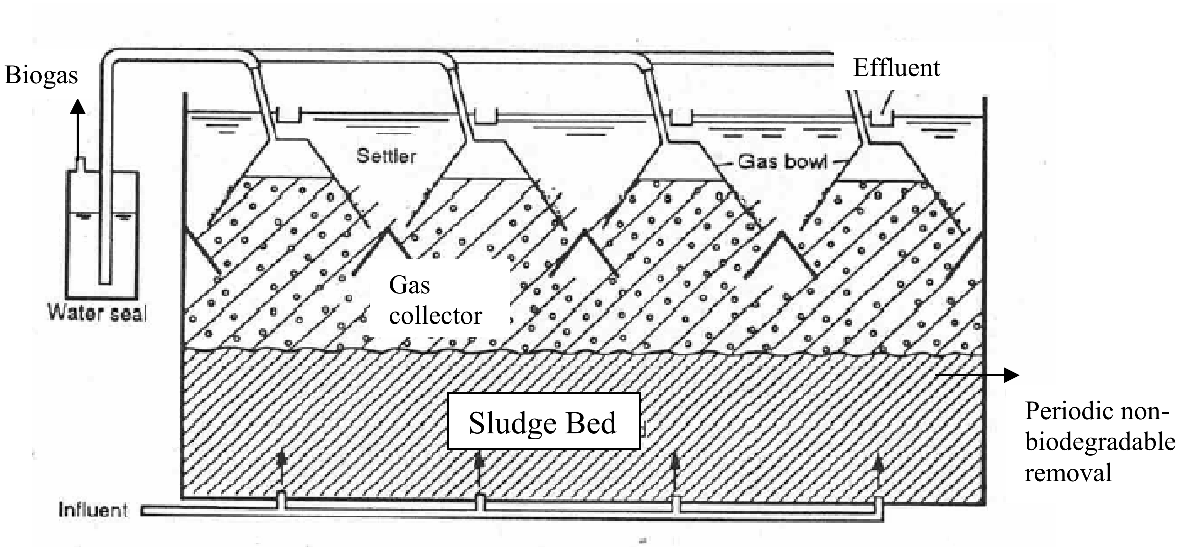


Fig. H-6. Schematic of a UASB Bioreactor[300]

In the UASB, the inflowing organic acids and solids come in contact with the methanogenic microbial community residing in the reactor. The microbes selectively form themselves into discrete "granules" that, collectively, have very high surface area and mass transport capability. The microbe granules take in the organic acids and produce methane as a metabolic product. The granules and biomass solids arriving as influent are suspended and mix in the sludge blanket by movement of biogas bubbles that float upward.

An advantage of UASB is that solids retention time (SRT) and hydraulic retention time (HRT) are decoupled. For the ArrowBio process UASB reactor, SRT is on the order of 75 days while HRT is about 1 day. The low HRT translates to relatively small reactor volumes, while long SRT generally provides for more complete biodegradation and high rates of methane production.

Table H-5 shows the projected mass balance and electricity production from a California waste stream as provided in the survey response. Moisture content of the biodegradable portion of the waste stream was adjusted from that used in the survey response (from 40% to 30%). In addition, while UASB reactors can produce biogas with relatively high methane concentration, the 75%(vol.) value claimed by ArrowBio seems high. Independent evaluation or test results are needed to corroborate this. For the material balance, methane concentration was adjusted to 65%. The survey indicates that approximately 80% of the biomass (dry matter or TS) is consumed in the biological reactors, which also is rather high. Approximately 7-15% of TS is inert ash and another 10-15% is non-biodegradable lignin (depending on waste stream). This leaves 70-83% of the biomass dry matter that is biodegradable (representing upper limits for a perfect system). Finally, the material balance could not be closed using the information provided (that is, about 15% of the mass could not be accounted for in the products).

Table H5. Mass Balance and Power Production for ArrowBio Process [a]

		Tons per year	% of Input
	Waste Input	200,000	100
Outputs	Recovered (Non Biodegradable)	35,330	17.7
	Soil Amendment (50% water)	40,890	20.4
	Biogas		
	CH_4 (26.6 Mm^3, 65% of total biogas volume)	20,943	
	CO_2	31,012	
	Biogas Total	51,956	26.0
	Water	23,340	11.7
	To Landfill	18,720	9.4
	Total Outputs	170,235	85.1
	Unaccounted	29,765	14.9
	Electrical Production	Gross	Net
	MW	10.3	8.8
	kWh/ton (unsorted)	451	385
	kWh/ton (material to digester)	618	528

a) Based on ArrowBio survey response using Santa Barbara RFQ waste stream and 35% efficiency for electricity generation.

The ArrowBio process seems an attractive method for processing and converting MSW based on the limited information made available. The process can accept any additional anaerobically biodegradable feedstocks that are collected separately or are outside the standard MSW stream including food processing and restaurant wastes, activated sewage sludge, and biodegradable industrial waste waters. More information including real operating data from the existing facility in Israel would be helpful for assessing the process. Certain claims must be met with skepticism until proven with real data. These include the methane production and its high concentration in the biogas, the high extent of biodegradation claimed (80% of total solids), and the amount of inert materials separated in the water-vat process.

UC Davis anaerobic phased solids digester

This system was developed and patented by Professor Ruihong Zhang and Dr. Zhiqin Zhang from UC Davis (Zhiqin Zhang is currently at the California Energy Commission).[301] The system is licensed to Onsite Power Systems for commercialization. Laboratory and pilot scale reactors are located at UC Davis.

A facility is proposed for a site on the California State University at Channel Islands campus. The facility would process 250 TPD of green waste diverted from Ventura County landfills and presumably some waste from the campus. It should produce sufficient biogas for generating 2 MWe of power. A byproduct would be 25-50 TPD of fertilizer. The capital cost of the project is reported to be $12 million ($6,000/kW installed). Revenues from the project include the price of the energy displaced by the facility, fertilizer sales, and tipping fees from waste hauled in from off campus. The facility would operate at the thermophilic temperature (135º F) and have a solids retention time of 12 days.

The anaerobic phased-solids (APS) digester decouples solid-state hydrolysis and acetogenic fermentation from the methane producing fermentation, allowing for separate optimization of the two processes. The two reactors are connected through a closed liquid recirculation loop that transfers the soluble material released in the hydrolysis reactor to the biogas producer (methanogenesis) (See Figure H-7). The biogas reactor can be designed for relatively short liquid retention time by using suspended growth, attached growth, anaerobic moving bed reactor (AMBR), or upflow anaerobic sludge blanket (UASB) reactor types.[302]

The hydrolysis reactor can accept high solids feedstock that, depending on its characteristics, may need some kind of pretreatment such as shredding to increase hydrolysis rate. The hydrolysis reactor operates in batch mode. Because of this batch operation, the concentration of the soluble compounds in the liquid being transported to the biogas reactor will vary from zero immediately after enclosing a fresh batch of feed in the hydrolysis vessel to a maximum when the rate of hydrolysis is highest. The soluble compound concentration will then taper off as the remaining soluble biomass declines. Correspondingly, the biogas production rate will vary from low to high to low again because it depends on the strength and rate of the inflow liquid arriving from the hydrolysis stage.

By using several batch-loaded hydrolysis reactors, the loading of each being timed (or phased) one after another such that the strength of solubilized biomass flowing from all hydrolysis reactors will have an overall average that is more stable (or smooth if charted against time; see Figure H-8).

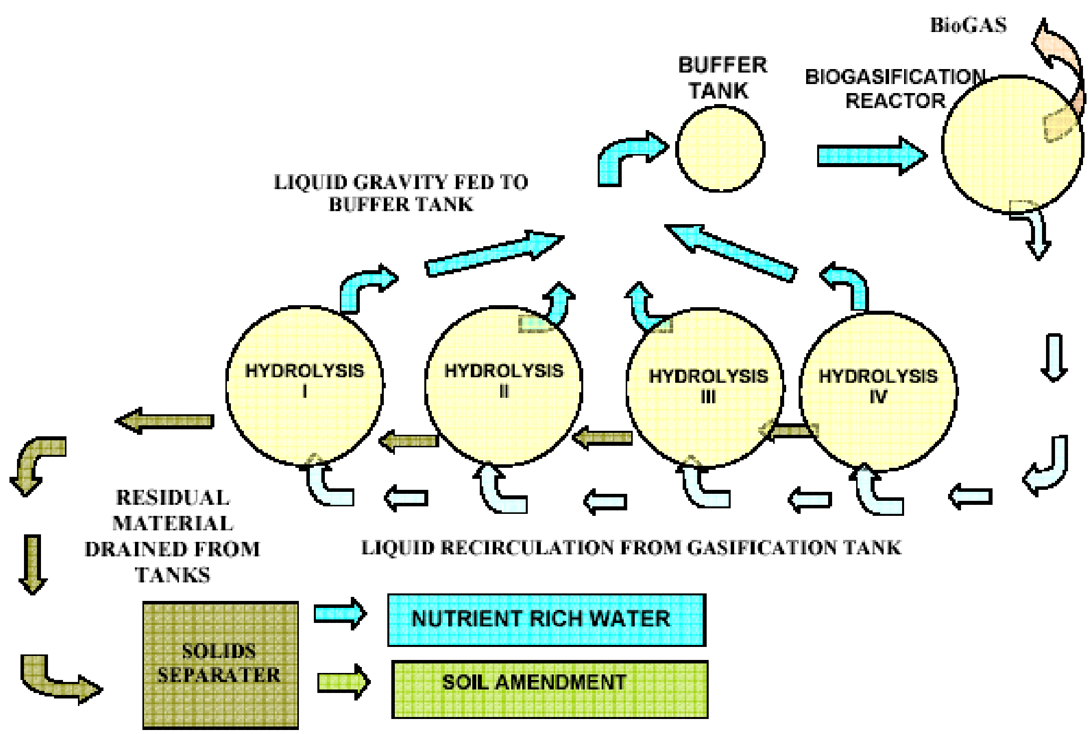


Fig. H-7. Schematic of APS Digester System Showing 4 Hydrolysis Vessels (Courtesy R. Zhang)

This relatively stable average strength liquid allows for suitable size and design of the single biogas reactor in order to optimize the methanogenic portion of the process.

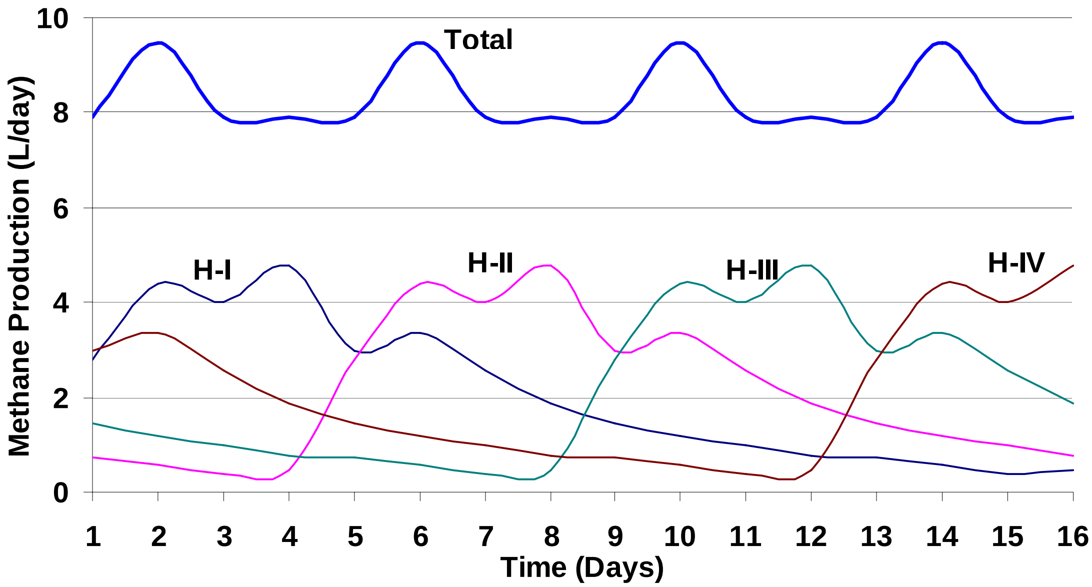


Fig. H-8. Simulated Biogas Production Rate for Lab-Scale APS Digester System

BRI Energy, LLC (Fayetteville, Arkansas)

BRI is marketing technology based on Dr. James I. Gaddy's research in bioengineering. More than 15 years ago, he isolated bacteria that can be used uniquely for digestion processes. These bacteria metabolize synthesis gas and emit ethanol as a product. The BRI technology is a hybrid thermochemical and biochemical conversion system (see Figure H-9). A gasifier is used to create a synthesis gas that is injected into the bioreactor where ethanol is produced. BRI claims that 75–80 gallons of ethanol and 160 kWhe per dry ton of biomass can be produced. (With used tires as fuel, this is doubled to 150 gallons per dry ton). BRI claims that the process takes less than seven minutes from feeding into the gasifier to the production of ethanol. By contrast, standard methods for sugar fermentation require 36–48 hrs.

Co-products of the process include heat[§§] and hydrogen.

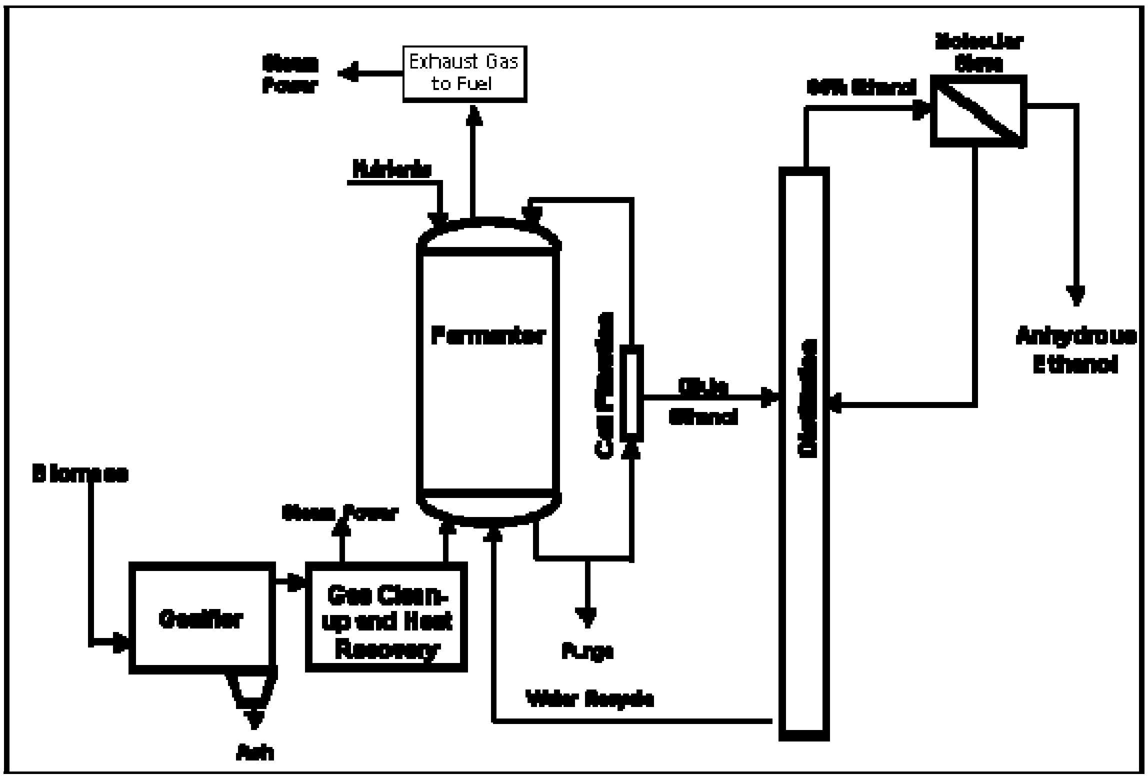


Fig. H-9 Schematic of BRI gasification and fermentation of ethanol process (Source: BRI)

This process consumes 90 to 95% of the carbon-based feedstock, leaving a residue of non-hazardous ash. BRI reports that the bacteria used have a health hazard rating of "Level 1," the lowest possible rating for any microorganism. BRI claims to create no environmental or health hazards, no ground or water contamination, and emissions that are easily controllable.

There is one pilot facility in Fayetteville, Arkansas. Currently, this plant is processing salt water-immersed wood from Alaska.

BRI reports that several demonstration projects are being negotiated (see Table H-6).

[§§] The gasifier operates at 2000^{o} C and the synthesis gas must be cooled to 100^{o} C before entering the bioreactor.

Table H-6. Ongoing and Potential BRI Demonstration Projects

Location	*Waste Type*	*Operation*	*Status*
Fayetteville, NC	Salt water-immersed wood	Ethanol Production	Currently running
San Joaquin Valley	Agricultural Waste	Waste Disposal; Ethanol/Energy Production	In negotiation
Los Angeles County	Sludge from Hyperion Plant	Waste Disposal; Ethanol/Energy Production	In negotiation
Minnesota	Corn stover from ethanol plant	Energy Production	Final negotiations
Galesburg, IL	Railroad ties and corn stover	Waste Disposal; Ethanol/Energy Production	In negotiation

Bioconverter (Santa Monica, CA)

The company is part of McElvaney Associates Corporation. McElvaney has developed and patented (U.S. Patent no. 6,254,775) an AD system that can be characterized a single-stage low solids fixed (immobilized) film anaerobic digester. Recent announcements indicate the company has negotiated a 20-year agreement to provide the Los Angeles Department of Water and Power with electricity from the bioconversion of green wastes for the amount of $16 million per year ($48/MWh).

The facility will begin operation in 2008 and consume 3,000 TPD of Los Angeles green waste and generate 40 MW of electricity. Other costs to the city for the project are unknown (presumably, a tipping fee will be also be paid to Bioconverter for disposal of the feedstock). Approximately 1,000 TPD of digester residue will be created, which potentially can be used in compost operations or as soil additives. If no market exists for the material, it will likely be disposed in landfills.

Another announced project is with the City of Lancaster, California. A $16 million facility is proposed to convert 200 TPD of local green waste and produce 5,000 gallons per day of compressed natural gas (CNG) that can be used as a transportation fuel. Press releases claim that digester residue will be used in poultry feeding operations. The project will pursue alternative fuel and air pollution reduction-related grants through the local air pollution control district, but otherwise the facility is expected to be funded privately.

The feed material is primarily green waste and source-separated food wastes. The process can also accept waste paper (magazines and junk mail, mixed residential, etc.), FOG (fats, oils, and grease), and "high-strength" wastewaters. Feed is comminuted as necessary and liquid added to obtain a slurry with TS of ~10%. Gas and liquid are recirculated in digester to promote mixing.

The single stage digester relies on fixed support matrix of polyethylene for growing and immobilizing the methanogenic microorganisms. Reactor liquid and biogas are recirculated through the medium to maintain solids suspension. The system is probably operated in the mesophilic temperature range (95º F) because solid retention time is approximately 30 days. Products are typical for AD systems and include methane and solid and liquid soil amendments/fertilizers.

Table H-7 shows basic information for the two proposed Bioconverter projects (LADWP and City of Lancaster). The table shows simple energy conversion efficiency (energy in product/energy in feedstock) using a high and low estimate for feedstock energy content. The estimated efficiencies range from about 10 to 20% (depending on feedstock characteristics). These estimates are reasonable but tend towards the optimistic end of the range expected from AD systems.

Systems have been installed in the Caribbean (see http://www.dwacaribbean.com/articles.html) and Hawaii. In Hawaii, a 2 TPD system operated on food and green waste for four years with some sale of liquid fertilizer. The company cooperated with the UNISYN system in Waimanalo, Hawaii, which used feedstock including manure from 2,000 cows, 250,000 poultry layers (egg laying hens)and waste from a USDA fruit fly rearing facility. The system was co-located with the animal operations as well as a greenhouse. Residue from the digesters was used as protein supplement in the poultry operation and aquaculture. The facility transitioned to processing food and grease wastes and was closed in 1999.

Table H-7. Basic Bioconverter Project Input and Output Capacities.

Project	Green waste feed rate (Tons/day)	Capital cost ($M)	Payment from Agency ($million/year)[a]	Energy in feedstock (GJ / day)		Product		Energy in Product (GJ/ day)	Efficiency of Conversion (%)	
				High[b]	Low[c]	Electricity MWe	CNG (gallons/day)[d]		Low[c]	High[b]
LADWP	3000	?	16	30395	15997	40	-	3456	11.4	21.6
Lancaster	200	44	?	2026	1066	-	5000	198	9.8	18.6

a) $48 /MWh.
b) 11.4 MJ/kg assuming all prunings, trimmings, branches (@40% moisture).
c) 6 MJ/kg assuming all leaves and grass (@ 60% moisture).
d) Assumes compressed to 3,600 PSI, with volumetric energy density equal to 30% that of gasoline.

Valorga (Montpellier, France)

The Valorga process was designed to treat organic solid waste. It is an anaerobic digestion process and accepts MSW after appropriate separation of recalcitrant fraction. The process dilutes and pulps the organic fraction to about 30 percent solids content. This is considered a high solids process. Steam is used for heating/maintaining temperature in the reactors as necessary. Mesophilic or thermophilic systems are used depending on feedstock and economics.

The reactor is a continuous one-step plug-flow process. The reactor consists of a vertical outer cylinder with an inner wall on about the 2/3 diameter of the outer one. Material enters at the bottom on one side of inner wall and must flow up one side and down the other side before it can exit.[303] The retention time is approximately three weeks. Biogas is injected in the base of the reactor and the bubbles serve as a means for mixing and keeping solids suspended (gas-mixed). The digestate is dewatered and can be composted. Table H-8 lists existing facilities.

Table H-8. Valorga Process Installations[304]

Location		Material	Capacity (ktonnes/y)	Start-up Date
Bottrop	Germany	Kitchen waste	6.5	1995
Geneva	Switzerland	Kitchen/Green waste	10	2000
Engelskirchen	Germany	Kitchen/Green waste	35	1998
Freiburg	Germany	Kitchen/Green waste	36	1999
Tilberg	The Netherlands	Kitchen waste	52	1994
Bassono	Italy	Sorted MSW/sludge	55	2003
Mons	Belgium	Sorted MSW	59	2002
Amiens	France	Sorted MSW	85	1988
Varennes-Jarcy	France	Sorted MSW	100	2002
Cadiz	Spain	Sorted MSW	115	2002
Barcelona	Spain	Sorted MSW	120	2004
Hanover	Germany	Sorted MSW/sludge	125	2002
La Coruna	Spain	Sorted MSW	142	2001

Wehrle Werk AG (Emmendingen,Germany)

Biopercolat Process

Wehrle Werk AG is large company with activities in thermal conversion of biomass and MSW, including several MSW combustion facilities. The company is also active in wastewater treatment, which has led to involvement in the solid waste digestion facility at Kahlenberg (2000 t/y) using the Biopercolat process.

The Biopercolat process is a multi-stage high solids process (see Figure H-10).[305] The first hydrolysis stage is carried out under partial aerobic conditions (microaerophilic) as a means to increase the rate of hydrolysis. Process water is continually percolated through the mechanically agitated (and slightly aerated) hydrolysis chamber (a horizontal tunnel much like the Wright MBT system). The leachate hydrolysis water is fed to an anaerobic plug flow filter filled with support material operating as an upflow anaerobic blanket sludge (UASB) reactor. The process has a retention time of only seven days.

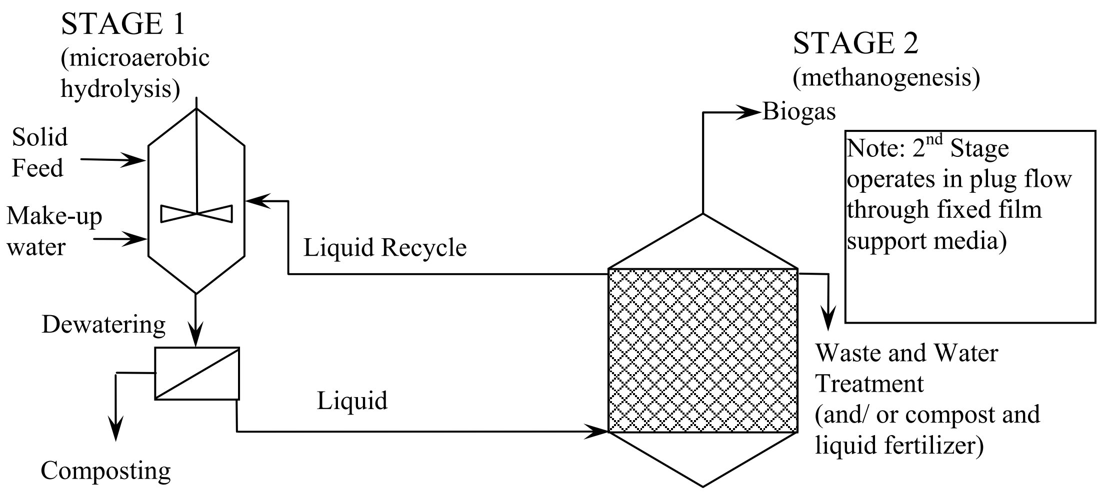


Fig. H-10. Simple Schematic of Biopercolat Process (high solids 1st stage, low solids 2nd stage) Adapted from Mata-Alvarez, J. (2003)

Wright Environmental Management (Ontario, Canada)

The company supplies "in-vessel" composting systems. These are managed and accelerated aerobic conversion processes. The material is loaded into a tunnel like enclosure and moves slowly in plug flow fashion. Any leachate is recirculated, and air is actively pumped through the material throughout the length of the enclosure. In situ mixing and moisture management results in a 10–14 day retention time for material. Excess air and gaseous products can be fed through a biofilter for odor control before release to the environment. The system is modular, and capacities can be scaled from 600 lbs to 30 TPD through one enclosure tube.

MSW can be processed after appropriate separation of non-compostable material.

The company lists several reference plants, including the following:

- Aberdeenshire, Scotland: 32,000 TPY MSW.
- Isle of Wright, U.K.: 22,000 TPY mixed food/green waste.
- Dept. of Corrections, Powhatan, Virginia: 730 TPY food waste.
- Dept. of Corrections, Ogendburg, NY: 730 TPY food waste.
- Allegheny College, Pennsylvania: 365 TPY food waste.
- Albany, NY: 18,250 TPY organic fraction MSW.

CiTec (Finland/Sweden)

CiTec is a group of Finnish and Swedish companies with the majority of operations originating from the office in Vaasa, Finland.

The Waasa process.

This is a single stage "wet" (total solids <15%) anaerobic digestion system. Figure H-11 displays a schematic of the process. For the organic fraction of MSW to be used in this system, it must undergo pretreatment in a pulper that shreds, homogenizes, and dilutes the material to the desired concentration of total solids (10-15% TS). Recycled process water and some fresh make-up water is used in the dilution. The slurry is then digested in large "complete mix" (completely stirred) reactors.

The pretreatment required to obtain adequate slurry quality while removing coarse or heavy contaminants is complex and inevitably incurs a 15-25 % loss of volatile solids.[306] Mechanical impellers and injection of a portion of the biogas into the bottom of the reactor tank are used to keep the material continuously stirred and as homogenous as possible.

To reduce short-circuiting of the feed,[***] a pre-chamber is used. Fresh material from the pulper enters the pre-chamber along with some of the biomass from the main tank for inoculation. The pre-chamber operates in plug flow requiring a day or two before the material makes its way into the main reactor, thus ensuring all material entering the process has a few days of retention time guaranteed. Even with the pre-chamber arrangement, enough short-circuiting occurs that all pathogens are not eliminated, requiring a pasteurization step in the pretreatment. Typical pasteurization uses steam injected in the pulper to maintain feed at 70º C for one hour.

The process can be operated at both thermophilic and mesophilic temperatures. The plant at Vaasa uses both temperature ranges in parallel (the thermophilic process has a retention time of 10 days; the mesophilic, 20 days). Process performance parameters (from manufacturer's summary data) include gas production in the range 100-150 m^3/tonne of bio-waste added (20-30% of the gas is used for internal heat requirements), residue volume reduction of 60%, and residue weight reduction 50-60% The digestate can be further treated by aerobic composting, but this depends on the waste quality.

Several plants are operational in Europe and Japan based on the Waasa process. Capacities range from 3,000–90,000 tonnes per annum (see Table H-9).

Table H-9. List of Waasa Process AD Sites[307].

[***] Short-circuiting of feedstock occurs when fresh material is introduced to a complete mix continuous flow reactor. A feature of a complete mix reactor is that material is dispersed quickly and evenly throughout (zero concentration gradient). A portion of fresh material will, therefore, pass quickly through the reactor (short-circuit) without having sufficient time to biodegrade.

Waasa (CiTec) System Locations		Feedstock	Scale (t/yr)	Temp. (ºC)	Year began Operation	Status	Output Elect. (kWe)	Output heat (kWth)
Kil	Sweeden	Biowaste	3000	55	1998	Operational	0	228
Vaasa	Finland	MSW	15000	55	1994	Operational	300	620
Pinerolo	Italy	MSW /Sludge	30000*	55	2003	Completion	1200	1880
Groningen	The Netherlands	MSW	85000*	55	1999	Operational	1920	3000
Friesland	The Netherlands	MSW	90000*	55	2002	Start-up	2000	3140
Tokyo	Japan (Ebara)	Biowaste/Sludge	500	55	1997	unknown		
Ikoma	Japan (Ebara)	Biowaste/Sludge	3000	55	2001	unknown		
Shimoina	Japan (Ebara)	Biowaste/Sludge	5000	37	2001	unknown		
Jouetsu	Japan (Ebara)	Biowaste/Sludge	12000	55	2001	In operation		

* From pretreatment

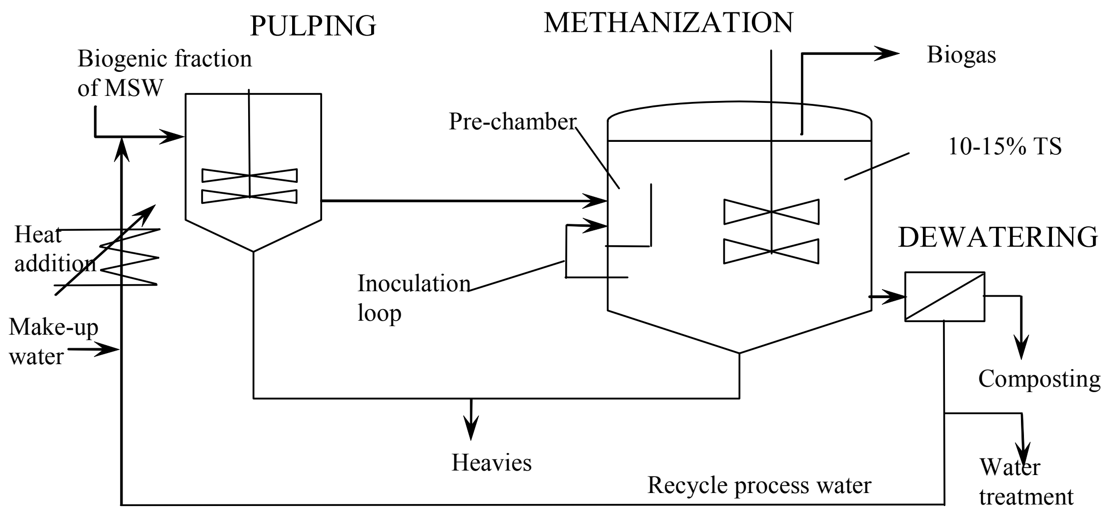


Fig. H-11. Schematic of Single-Stage Low Solids Anaerobic Digestion System (Waasa, Finland) Adapted from Mata-Alvarez, J. (2003)

Linde-KCA-Dresden GmbH (Dresden, Germany)

Linde-KCA is a large engineering design/build firm active in pharmaceuticals, chemical, and wastewater and solid waste treatment.

The company is active in both low and high solids (wet and dry) digestion systems (see Figures H-12 and H-13), and mechanical-biological treatment systems (MBT)for separated MSW. MBT systems include aerobic composting systems with mechanical manipulation of the feedstock and intensive aeration. Some systems include intensive aerobic digestion as a preprocess for a feedstock that is later anaerobically digested. The company reports it was the designer-builder of the world’s largest compost facility in Bangkok, Thailand, with an output of 1,200 TPD.

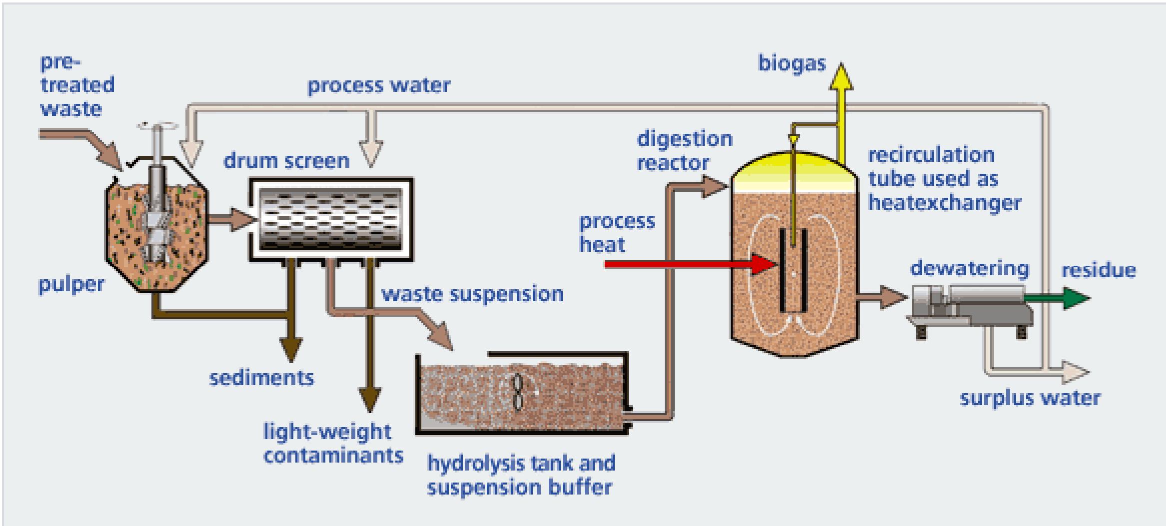


Fig. H-12. Linde-KCA two stage wet digestion system (source Linde-KCA)

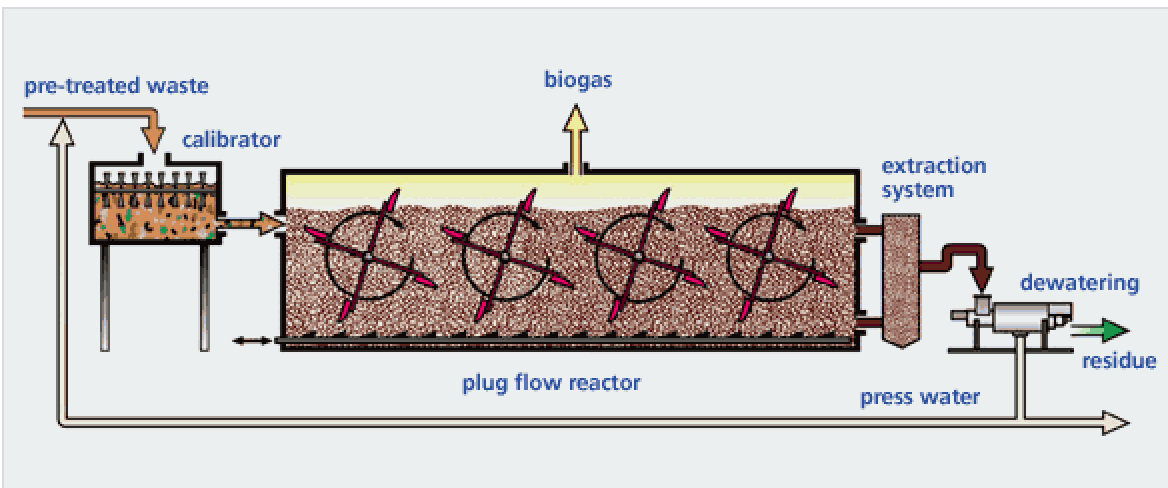


Fig. H-13. Linde-KCA dry digestion plug flow system (source: Linde-KCA)

Linde has designed, built, and operated a facility in Radeberg, Germany which co-digests source-separated biogenic wastes from household and industrial sources, along with sewage sludge from wastewater treatment. The company reports that this co-digestion concept enhances degradation of the sewage sludge component of the feedstock (increases biogas production from the sewage sludge) and results in decreased capital and operating costs compared to those for two separate facilities.

Another co-digestion facility designed and built by Linde is located on a dairy farm in Behringen Germany. The plant takes the low solids manure and codigests with grease from restaurant grease traps, solids from pig manure, and range of other food processing waste including brewery sludge, rape seed press cake, and low-grade seed potatoes. The facility processes about 100 TPD (wet), of which 75% is dairy cow manure. The facility produces about 650 kW from two Jenbacher 450 kW gensets. Thirty percent of the power production is used on-site for operating the plant and the dairy with the balance sold to the grid.

Recent orders for company projects include a mechanical-biological integrated waste treatment plant to be located at the landfill in Leipzig-Crobern. The facility will include material separation and recovery. The capacity will be 300,000 TPY. One-third of the material will be recycled; one-third, thermally converted; and one-third, treated biologically. Residues from the thermal and biological treatments will be landfilled.

Another mechanical-biological waste treatment plant has been ordered for Fridhaff, Luxemburg.

Projects currently under construction include:

- Municipal Solid Waste Treatment Plant ECOARC I in Barcelona, Spain: wet pretreatment, anaerobic digestion and composting of MSW.
- Municipal Solid Waste Treatment Plant PINTO in Pinto/Madrid, Spain: wet pretreatment, anaerobic digestion and compositing for MSW.
- Biowaste Treatment Plant, Lisbon, Portugal: organic fraction of MSW.

Kompogas (Glattbrugg, Switzerland)

This Swiss company has several units operating or planned throughout Europe. Plants are also operating or planned in Japan, and a facility in Martinique is under construction (approximately 25 operating or planned plants).

The process is optimized on green waste and kitchen waste for fermentation to biogas. The biogas will run small engines for heat and power. In some cases, it is upgraded to natural gas standards (remove CO_2 and H_2O and other diluents). The upgraded biogas goes into Switzerland's well-developed natural gas vehicle fueling systems, thus converting household organic wastes into a transportation fuel.

The Kompogas system is a high solids, thermophilic single-stage digestion system.[308] It can be classified as a mechanical biological treatment plant (MBT). The reaction vessel is a horizontal cylinder into which feed is introduced daily. Movement of material through the digester is in a horizontal plug-flow manner, with digested material being removed from the far end of the reactor after approximately 20 days. An agitator within the reaction vessel mixes the material intermittently. The digestate is dewatered, with some of the press water being used as an inoculum source and the remainder being sent to an anaerobic wastewater treatment facility which also produces biogas.

ISKA, U-plus Umweltservice AG (Ettlingen, Germany)

The ISKA Percolation process is used for the putrescible fraction of the waste stream. It involves a high degree of mechanical sorting/separating in the preprocessing steps as well as in the hydrolysis and digestion portions of the process. The process finishes with the dewatering of the digestate. This is classified as mechanical-biological treatment (MBT) of MSW.

Biodegradable material is first separated from the stream and then is subjected to a hybrid aerobic/anaerobic degradation process. The ISKA process uses aerobic means for hydrolysis of insoluble organic material to reduce the overall process (retention) time. After this percolation step, the material passes to standard anaerobic methods for production of biogas and reduction of mass. The digestate is then dewatered and sent to aerobic composting or is converted to energy or other products by thermal means.

According to ISKA,[309] the energy available from the biogas production is roughly sufficient to power the process. To create exportable energy, the dewatered digestate and the non-digested stream must be converted (thermally). ISKA also indicates that it is pretreating MSW and sending the residual solid to the SVS Schwarze Pumpe gasification facility which makes methanol and power from waste feedstocks.

The commercial-scale demonstration plant at Buchen, Germany, will be expanded (to 150,000 metric tons per year) to accept MSW from the Ludwigsburg area. The ISKA process was chosen for a new facility near Sydney, Australia. The capacity will be 170,000 metric tons per year at full build-out. Construction began in July 2003 (see below).

Sydney waste processing, resource recovery centre

Sydney's publicly owned waste management company, Waste Service NSW investigated alternative technologies and chose an advanced sorting and biochemical processing system offered by Global Renewables Ltd. (GRL) and Novera Energy.

The GRL process, 'UR-3R' is an integrated MSW plan for reduction, recovery, recycling (3R), and accepts the full waste stream including green and food waste. Essentially, it is a mechanical-biological (MBT) separation and conversion process utilizing advanced material sorting, the ISKA Percolation process, energy recovery (from biogas only), and composting.

The largest potentially useable product stream from the process is composted material (their term is Organic Growth Material , OGM) in the amount of ~20% of the input mass. The company claims that only about 11% of the mass of the input material will need landfill disposal (21% if ADC is included). See Table H9 (adapted from company charts)[310].

The facility is designed to accept 170,000 metric TPY of mixed household waste. Electrical production is estimated to be 17,500 MWh/y [311] (2.2 MWe based on 0.9 capacity factor). The Sydney 'UR-3R' facility is scheduled to begin start-up operations in August, 2004. The company is also involved in joint venture with the Taizhou municipality (China) to develop a similar system.

Table H-10. Category Breakdown of Input and Output Mass for the UR-3R Process

Waste Profile (Input to Process)	Wt. %		UR-3R Process Outputs	Wt. %	
Green Waste	32		Evaporation	31	
Food Waste	27		CO2	11	
Paper	12		Compost Matl.	20	
			Biogas	5	
			Paper	6	
Category Total		**71**	**Category Total**		**73**
Film Plastic	5				
Other Plastic	2				
PVC	1				
PET	1				
HDPE	1		Plastic	1	
Category Total		**10**	**Category Total**		**1**
Metals	3		Metals	3	
Glass	4		Glass	3	
Category Total		**7**	**Category Total**		**6**
Sand	2		Residuals	11	
Other	13		ADC	10	
Category Total		**15**	**Category Total**		**21**
Total	**103**		**Total**	**101**	

Eco Tec (Finland)

WABIO Process

This anaerobic digestion process is targeted for the MSW stream. The system includes receiving, sorting, mechanical preconditioning, digestion, and dewatering of the digestate for possible further composting processing.

The digestion process occurs in a single-stage low-solids reactor. It operates in the mesophilic temperature region.

Three plants in Europe are located in Vaasa and Forssa, Finland, and Bottrop, Germany (6,500 TPY source-separated waste).[312] Another Wabio AD facility is proposed for facility for the city of Kalyan, India. [313] The scale would be 55,000 TPY. No schedule is given for the project, and the status is unknown.

Organic Waste Systems (Gent, Belgium)

Dranco Process and Sordisep System

Organic Waste Systems (OWS) was established in 1988 and maintains biodegradability labs in Belgium and Ohio. OWS also has an exclusive partner in Japan for proposed facilities there. The company designs, builds, and operates AD plants for MSW. The company also consults on biodegradation and waste management.

OWS has developed the Dranco (Dry Anaerobic Composting) process as well as the Soridsep (Sorting – Digestion-Separation) integrated waste system. The technology is patented under international patent number WO 02102966.

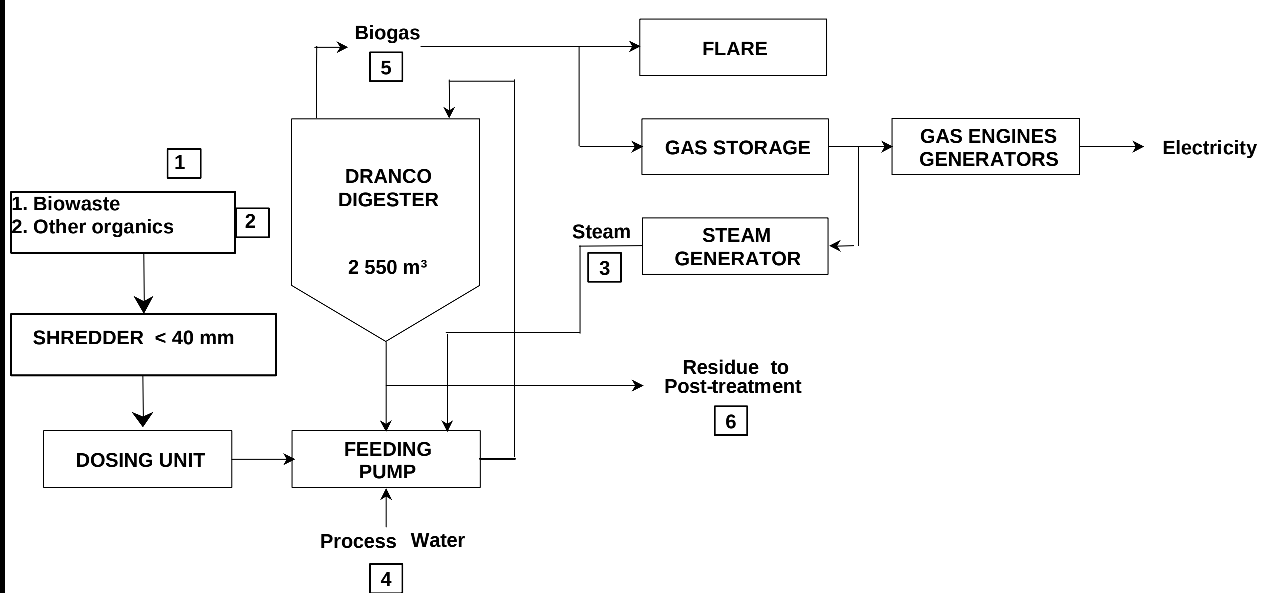
The Dranco process was developed in the late 1980s. It is a high-solids, (15-40% TS) single-stage anaerobic digestion system that operates at thermophilic temperatures.[314] Feed is introduced into the top of the reactor and moves vertically as plug flow. A portion of the digestate is recycled as inoculation material, while the rest is dewatered to produce an organic compost material. No mixing takes place within the reactor, other than that brought about by the downward, plug-flow movement of the waste and some gas bubbling upwards. Source-separated household and industrial wastes are preferred.

Existing commercial systems (see Table H-11) are reported to have biogas production rates in the range of 6–10 m^3 biogas per m^3 reactor volume per day (or about 120 m^3 biogas per wet ton of feedstock). The DRANCO process produces a compost product and heat or electricity from the biogas. The company reports electricity production can range from 0.1 to 0.3 MWh/ ton feedstock.

Figure H-14 shows a schematic with a mass balance for an operating DRANCO system. Figure H-15 shows some of the reactor detail.

Table H-11. Organic Waste Systems' Dranco References[315]

Dranco Process Locations		Scale (ktonne/y)	Year Began Operation
Brecht I	Belgium	20	1992
Salzburg	Austria	20	1993
Bassum	Germany	13.5	1997
Aarberg	Switzerland	11	1998
Villeneuve	Switzerland	10	1999
Kaiserslautern	Germany	20	1999
Brecht II	Belgium	50	2000
Alicante	Spain	30	2002
Rome	Italy	40	2003
Laeonberg	Germany	30	2004
Hille	Germany	38	2005
Münster	Germany	24	2005
Terrassa	Spain	25	2005
Pusan	South Korea	75	2005



	1	2	3	4	5	6
tons/year	22 500	7 500	1 200	6 900	7 050	31 050

Fig. H-14. Schematic and mass balance of the DRANCO process (source: OWS)

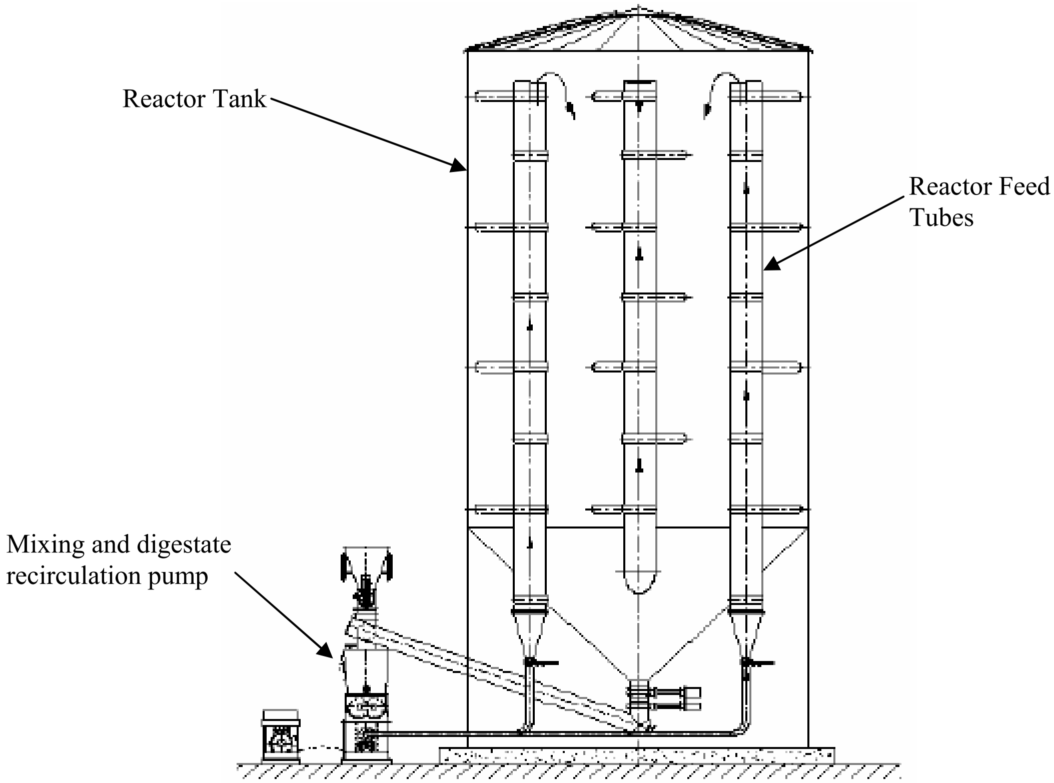


Fig. H-15. Drawing of the DRANCO reactor (source OWS)

BTA (Munich, Germany)

The BTA process uses single or multistage anaerobic digestion to treat the organic fraction of MSW, creating methane and compostable solid residue and a liquid residue marketed as liquid fertilizer. The process uses a "low solids" concentration slurry and can be operated in meso or thermophilic temperature ranges.

If source-separated biodegradable waste is not available, the process will include upfront sorting equipment. After sorting, the organic fraction is diluted to ~10% TS (low solids concentration) and digested in single or multiple stages depending on facility and waste stream requirements. BTA has licensed the process to MAT Müll- und Abfalltechnik, for Western Europe; to Biotec Sistemi, Genua, for Italy; and to Niigata Engineering, Tokyo, for Japan. An exclusive license for Canada and North America was given to Canada Composting, Newmarket/Ontario (CCI). Furthermore, several cooperation agreements were made with non-European partners.

BTA facilities are operating in Europe, Asia, and North America (see Table H-12).

Canada Composting operates a pilot facility in Toronto since September 2002 and is competing for a larger "full scale" system for the municipality. The Toronto pilot capacity is 25,000 TPY using source-separated organics. The 5.4-acre Newmarket Plant was operating for a period. It produced 5 MWe from burning the biogas in reciprocating internal combustion engines while consuming 2 MWe, for a net electrical production of 3 MWe. Capacity was 150,000 metric tonnes per year. The

Newmarket plant, now operating, has been sold to Halton Recycling Limited (HRL) of Burlington, Ontario.

Table H-12. BTA Process References (Source; BTA)

BTA Process Locations		Scale (ktonne/y)	Year began Operation
Ko-Sung	Korea	3	2003
Karlsruhe	Germany	8	1996
Mertingen	Germany	11	2001
Erkheim	Germany	11.5	1997
Dietrichsdorf	Germany	17	1995
Waden-Lockweiler	Germany	20	1998
Kirchstockach	Germany	20	1997
Elsinore	Denmark	20	1991
Mülheim	Germany	22	2003
Toronto	Canada	25	2002
Villacidro	Italy	45	2002
Ieper	Belgium	50	2003
Newmarket	Canada	150	2000
Planned or under construction			
Alghoba	Libya	11	?
Krosno	Poland	30	~ 2005
Pamplona	Spain	100	~2005

Bibliography

[1] http://www.leginfo.ca.gov/pub/01-02/bill/asm/ab_2751-2800/ab_2770_bill_20020920_chaptered.html

[2] <http://www.epa.gov/fedrgstr/EPA-WASTE/2002/March/Day-25/f7097.htm>

[3] <http://www.netl.doe.gov/coalpower/gasification/description/gasifiers.html>

[4] <http://www.gasification.org/>

[5] Ratafia-Brown, J., Manfredo, L., Hoffmann, J., and Ramezan, M., *Major Environmental Aspects of Gasification-Based Power Generation Technologies—Final Report*, DOE/NETL, SAIC, 2002.

[6] http://www.eia.doe.gov/glossary/glossary_g.htm

[7] http://www.eere.energy.gov/consumerinfo/glossary.html

[8] http://www.nrel.gov/chemistry_bioenergy/bgcc.html

[9] Ciferno, J.P., and Marano, J.J., *Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production,* E2S/DOE-NETL, 2002.

[10] Bridgwater, A.V., "The Thermochemical Processing System," *Thermochemical Processing of Biomass*, A. V. Bridgwater, London, Butterworths: page 35–52, 1984. Bridgwater is a longtime and well-respected researcher in thermochemical conversion of biomass via primarily pyrolysis. He runs the European based Gasnet and Pyne (gasification and pyrolysis interest networks) in Aston University, UK.

[11] American Heritage Dictionary, 2000.

[12] <http://europa.eu.int/comm/environment/wasteinc/newdir/2000-76_en.pdf>

[13] Heermann, C., Schwager, F. J., and Whiting, K. J. (2001). "Pyrolysis & Gasification of Waste: A worldwide technology and business review." Juniper Consultancy Services LTD.

[14] Malkow, T., *Waste Management*, Vol. 24, 2004, pp. 53–79.

[15] Bryce, W.B., and Livingston, W.R., *The Current Status of the Mitsui R21 Process for the Advanced Thermal Processing of Municipal Solid Waste*, Mitsui Babcock, Renfrew, Scotland, 2003.

[16] Heermann, C., Schwager, F. J., and Whiting, K. J. (2001). "Pyrolysis & Gasification of Waste: A worldwide technology and business review." Juniper Consultancy Services LTD

[17] Malkow, T., *Waste Management*, Vol. 24, 2004, pp. 53–79.

[18] <http://www.wastegen.com/template.htm>

[19] WasteGen, UK, Company Overview and Background, Leicestershire, UK.

[20] Supplemental information provided by International Energy Solutions, Romoland, California.

[21] Heermann, C., Schwager, F. J., and Whiting, K. J. (2001). "Pyrolysis & Gasification of Waste: A worldwide technology and business review." Juniper Consultancy Services LTD

[22] Supplemental information provided by Balboa Energy Technologies.

[23] Heermann, C., Schwager, F. J., and Whiting, K. J. (2001). "Pyrolysis & Gasification of Waste: A worldwide technology and business review." Juniper Consultancy Services LTD

[24] Survey information provided by Graveson Energy Management.

[25] Survey and supplemental information provided by North American Power Company, Las Vegas, Nevada.

[26] Heermann, C., Schwager, F. J., and Whiting, K. J. (2001). "Pyrolysis & Gasification of Waste: A worldwide technology and business review." Juniper Consultancy Services LTD ,

[27] Malkow, T., *Waste Management*, Vol. 24, 2004, pp. 53–79.

[28] Supplemental information provided by Thide.

[29] Heermann, C., Schwager, F. J., and Whiting, K. J. (2001). "Pyrolysis & Gasification of Waste: A worldwide technology and business review." Juniper Consultancy Services LTD

[30] Malkow, T., *Waste Management*, Vol. 24, 2004, pp. 53–79.

[31] Supplemental information provided by Thide Environmental, Voisins-Le-Bretonnex, France.

[32] Heermann, C., Schwager, F. J., and Whiting, K. J. (2001). "Pyrolysis & Gasification of Waste: A worldwide technology and business review." Juniper Consultancy Services LTD

[33] Malkow, T., *Waste Management*, Vol. 24, 2004, pp. 53–79.

[34] Supplemental information provided by Thide Environmental, Voisins-Le-Bretonnex, France.

[35] Heermann, C., Schwager, F. J., and Whiting, K. J. (2001). "Pyrolysis & Gasification of Waste: A worldwide technology and business review." Juniper Consultancy Services LTD

[36] Malkow, T., *Waste Management*, Vol. 24, 2004, pp. 53–79.

[37] Supplemental information provided by Conrad Industries, Chehalis, Washington.

[38] Heermann, C., et al., 2001.

[39] Ibid

[40] Malkow, T., *Waste Management*, Vol. 24, 2004, pp. 53–79.

[41] Supplemental information provided by SERPAC Environment, L'Arbresle Cédex, France.

[42] Heermann, C., et al., 2001.

[43] Malkow, T., *Waste Management*, Vol. 24, 2004, pp. 53–79.

[44] Heermann, C., et al., 2001.

[45] Bridgewater, A.V., and Peacocke, G.V.C., "Fast Pyrolysis Processes for Biomass," *Renewable and Sustainable Energy Reviews*, Vol. 4, 2000, pp. 1–73.

[46] Heermann, C., et al.,, 2001.

[47] Bridgewater, A.V. and Peacocke, G.V.C., "Fast Pyrolysis Processes for Biomass." Renewable and Sustainable Energy Reviews, Vol. 4, 2000, pp. 1–73.

[48] Survey and supplemental information provided by Renewable Oil International, Florence, AL.

[49] Heermann, C., et al., 2001.

[50] <http://www.btgworld.com >

[51] Survey and supplemental information provided by JF BioEnergy Inc, Vancouver, Canada.

[52] Heermann, C., et al., 2001.

[53] Ibid

[54] Ibid.

[55] Ibid.

[56] Survey and supplemental information provided by Environmental Waste International, Ontario, Canada.

[57] Heermann, C., et al., 2001.

[58] Survey and supplemental information provided by ACM Polyflow Inc., Akron, OH.

[59] Heermann, C., et al., 2001.

[60] Ibid.

[61] Survey and supplemental information provided by Hebco International Inc.

[62] Bridgewater, A.V. and Peacocke, G.V.C., "Fast Pyrolysis Processes for Biomass," *Renewable and Sustainable Energy Reviews*, Vol. 4, 2000, pp. 1–73.

[63] Ibid.

[64] Supplemental information provided by Ande Scientific, Smethwick,Warley, W. Midlands, UK.

[65] Heermann, C., et al., 2001.

[66] Survey and supplemental information provided by ACM Polyflow Inc., Akron, Ohio.

[67] R. Odell, "Tire pyrolysis inventor designs a new device," *Bendbulletin.com,* <http://www.Bendbulletin.com> (March 29, 2004).

[68] Heermann, C., et al., 2001.

[69] Ibid.

[70] Malkow, T., *Waste Management*, Vol. 24, 2004, pp. 53–79.

[71] <http://www.interstatewastetechnologies.com>

[72] Survey information provided by Interstate Waste Technologies, Malvern, Pennsylvania.

[73] Calaminus, R. and R. Stahlberg, "Continuous In-line Gasification/Vitrification Process for Thermal Waste Management: Process Technology and Current Status of Projects," *Waste Management*, Vol. 18, 547-556, 1998.

[74] "The Karlsruhe Garbage Miracle Threatens to Close" < http://taz.de/pt/2003/10/28/a0131.nf/text.ges,1>

[75] Heermann, C., et al., 2001.

[76] Malkow, T., *Waste Management*, Vol. 24, pp. 53-79, 2004.

[77] <http://home.t-online.de/home/PKA.DE/>

[78] Toshiba Press Release, "Toshiba strengthens waste treatment and recycling plant business-signs technology agreement with PKA of Germany," <http://www.toshiba.co.jp>

[79] Anon, "Evaluation of gasification and novel thermal processes for the treatment of municipal solid waste," *Rep. NREL/TP-430-2161*, National Renewable Energy Laboratory (NREL), Golden, CO, 1996.

[80] Anon, "Council Directive 96/61/EC of September 24, 1996 concerning integrated pollution prevention and control," *Official Journal of the European Communities Series L 257*, 1996, 26–40.

[81] Anon, "Compact system generates clean power from waste," *Modern Power Systems* 16 (9), 1996, 53–57.

[82] Higham, I., Palacios, I., Barker, N., "Review of BAT for New Waste Incineration Issues R&D technical Report HOCO410 Part 1 Waste Pyrolysis and Gasification Activities Final report," Rep. UK Environment Agency, *AEA Technology Environment*, Bristol, 2001.

[83] Hjelmar, O., "Waste management in Denmark," *Waste Management*,Vol. 16 (5/6), 1996, 389–394.

[84] Compact Power, 2002. <http://www.compactpower.co.uk/images/process_illus.gif>

[85] Heermann, C., F. J. Schwager, et al., *Pyrolysis & Gasification of Waste: A worldwide technology and business review*, Juniper Consultancy Services LTD, 2001.

[86] Malkow, T., *Waste Management*, Vol. 24, 2004, pp. 53-79.

[87] Supplemental information provided by Brightstar Environmental, Queensland, Australia.

[88] Hopkins, P., "SWERF costs energy developer $137m," *The Sydney Morning Herald*, September 3, 2003.

[89] http://www.wollongong.nsw.gov.au/yourcouncil/mediareleases/index_1806.htm (accessed 17 October 2004)

[90] Survey and supplemental information provided by ECN

[91] Ibid.

[92] Supplemental information provided by Alcyon Engineering SA.

[93] Heermann, C., et al., 2001.

[94] Ibid

[95] <http://www.ebara.ch/downloads/ebara_Referencelist_TwinRec_100203.pdf>

[96] <http://www.ebara.co.jp/en/>

[97] Heermann, C., et al., 2001.

[98] <http://www.ebara.ch/downloads/ebara_Referencelist_EUP_0103.pdf>

[99] Seifert et al., *Brenn-und Synthesegas aus Abfail. Spezial BWK/TU/Umwelt 10*, S14-S18, 1998b.

[100] Seifert and Buttker, "Stoffiche Abfallverwertung uber die Route Vergasung, Synthesesgasherstellung, Methanolgewinnung in der SVZSchwarze Pumpe GmbH, Beitrage zur DGMK-Fachbereichstagung Energetische unfd Stoffiche Nutzung von Abfallen und nachwachsenden Rohstofffen," *Velen/Westfalen (Autorenmanuskripte),* 10–12 April 2000, pp. 169–197, DGMK Deutsche Wissenschaftliche Gesellschaft fur Erdol, Erdgas und Kohle e.V. DGMK-Tagungsrbericht 2000-1, Hamburg, 2000.

[101] Liebner and Ulber, "MPG–Lurgi Multi Purpose gasification: Application in gas-gasification," *Gasification Technology Conference*, 8–11 October 2000, San Francisco, California, 2000.

[102] Richers et al., Programm zur Untersuchung thermischer Behandlungsanlagen fur Siedlungsabfall, Wissenschaftliche Berichte FZKA 6298, Forschungszentrum Karlsruhe GmbH, Karlsruhe, 1999.

[103] Anon, Konzepte fur die offentliche Abfallwirtschaft in Berlin Kurzbericht, Rep., Koln: DPU Deutsche Projekt Union GmbHBerliner Stadtreinigungsbetriebe, Berlin, 2000c

[104] SFA Pacific for USDOE National Energy Technologies Laboratory (NETL) http://www.netl.doe.gov/coalpower/gasification/models/models.html

[105] Klose et al., Beitrage zur DGMK-Fachbereichstagung Energetische und stofflicche Nutzung von Abfallen und nachwachsenden Rohstoffen, April 22–24, 1996, Velen/Westfalen (Autorenmanuskripte), pp. 309–320, Hamburg: DGMK Deutsche Wissenschaftliche Gesellschaft fur Erdol, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9603; ETDE-DE-576, 1996.

[106] Seifert et al., Beteiebserfahrungen und neue Entwicklungen zurkombinierten stoffichen und energetischenAbfallvertung in der Sekundarrohstoffverwertungszentrem Schwarze Pumpe GmbH (SVZ), Beitrage zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfallen und nachwachsenden Rohstoffen, April 20–22, 1998, Velen/Westfalen (Autorenmanuskripte), pp. 131–142, DGMK Deutsche Wissenschaftliche Gesellschaft fur Erdol, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9802, Hamburg, 1998a.

[107] Richers et al., Programm zur Untersuchung thermischer Behandlungsanlagen fur Siedlungsabfall, Wissenschaftliche Berichte FZKA 6298, Forschungszentrum Karlsruhe GmbH, Karlsruhe, 1999.

[108] Erdmann, C., Liebner, W., Seifert, W., "Lurgi's MPG and BGL gasifiers at SVZ Schwarze Pumpe status and experiences in IGCC application," *Gasification Technology Conference*, 17–20 October 1999, San Francisco, California, 1999.

[109] Anon., "BGL commissioning status," *Gasification Technology Conference*, 8–11 October 2000, San Francisco, California, 2000a.

[110] Schneider, J., Seifert, W., Buttker, B., Verwertung von Sekunda¨ rrohstoffen durch Vergasungstechnik im Verwertungszentrum Schwarze Pumpe, Beitra¨ ge zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfa¨ llen und nachwachsenden Rohstoffen, 22–24 April 1996, Velen/Westfalen (Autorenmanuskripte), pp. 45–67. DGMK Deutsche Wissenschaftliche Gesellschaft fu¨ r Erdo¨ l, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9603; ETDE-DE-576, Hamburg, 1996.

[111] Seifert and Buttker, "Stoffiche Abfallverwertung uber die Route Vergasung, Synthesesgasherstellung, Methanolgewinnung in der SVZSchwarze Pumpe GmbH, Beitrage zur DGMK-Fachbereichstagung Energetische unfd Stoffiche Nutzung von Abfallen und nachwachsenden Rohstofffen," *Velen/Westfalen (Autorenmanuskripte)*, 10–12 April 2000, pp. 169–197, DGMK Deutsche Wissenschaftliche Gesellschaft fur Erdol, Erdgas und Kohle e.V. DGMK-Tagungsrbericht 2000-1, Hamburg, 2000.

[112] Seifert, W., Buttker, B., Vierrath, H., *Brenn- und Synthesegas aus Abfall. Spezial BWK/TU¨ /Umwelt 10, S14–S18*, 1998b.

[113] Erdmann, C., Liebner, W., Seifert, W., "Lurgi's MPG and BGL gasifiers at SVZ Schwarze Pumpe status and experiences in IGCC application," *Gasification Technology Conference*, 17–20 October 1999, San Francisco, California, 1999.

[114] Olliver R.A., Wainwright J.M., Drnevich R.F., 2000. Application of BGL gasification of solid hydrocarbons for IGCC power generation, Gasification Technology Conference, October 8–11, 2000, San Francisco, California.

[115] Pickett, M.M.R., "Modeling the Performance and Emissions of British Gas/Lurgi-based Integrated Gasification Combined Cycle Systems," PhD thesis, North Carolina State University, Raleigh, North Carolina, 2000.

[116] Liebner and Ulber, "MPG–Lurgi Multi Purpose gasification: Application in gas-gasification," Gasification Technology Conference, October 8–11, 2000, San Francisco, California, 2000.

[117] Stambler, I., "Europe turning to gasification for disposal of solid and liquid wastes," *Gas Turbine World* Vol. 28, No. 6, 1998, pp. 29–36.

[118] Anon., "BGL commissioning status," *Gasification Technology Conference*, 8–11 October, 2000, San Francisco, California, 2000a.

[119] Erdmann, C., Liebner, W., Seifert, W., "Lurgi's MPG and BGL gasifiers at SVZ Schwarze Pumpe status and experiences in IGCC application," *Gasification Technology Conference*, 17–20 October 1999, San Francisco, California.

120 Olliver R.A., Wainwright J.M., Drnevich R.F. Application of BGL gasification of solid hydrocarbons for IGCC power generation. Gasification Technology Conference, October, 8–11, 2000, San Francisco, California.

[121] Erdmann, C., Liebner, W., Seifert, W., "Lurgi's MPG and BGL gasifiers at SVZ Schwarze Pumpe status and experiences in IGCC application," *Gasification Technology Conference*, October 17–20, 1999, San Francisco, California.

[122] Anon.,"BGL commissioning status," *Gasification Technology Conference*, 8–11 October, 2000, San Francisco, California, 2000a.

[123] Bailey, R.A., "Kentucky Pioneer Energy/Lima Energy, Ohio," *Gasification Technology Conference*, San Francisco, California, October 2001.

[124] LANL, 1999 <http://www.apt.lanl.gov/projects/cctc/factsheets/clnen/cleanedemo.html>

[125] NETL, 2002 <http://www.netl.doe.gov/coalpower/gasification/projects/tech-demo/cct/i%gcc.html>

[126] Richers et al., Programm zur Untersuchung thermischer Behandlungsanlagen fur Siedlungsabfall, Wissenschaftliche Berichte FZKA 6298, Forschungszentrum Karlsruhe GmbH, Karlsruhe, 1999.

[127] Erdmann, C., Liebner, W., Seifert, W., "Lurgi's MPG and BGL gasifiers at SVZ Schwarze Pumpe status and experiences in IGCC application," *Gasification Technology Conference*, San Francisco, California, October 1999.

[128] <http://www.nrel.gov/chemistry_bioenergy/staff_alpha.html#c>

[129] <http://www.usherbrooke.ca/gchimique/personnel/profs/chornet/>

[130] <http://www.enerkem.com/2002/pages_en/main_en1_ns.html>

[131] Raskin, N., Palonen, J., and Nieminen, J., *Power Boiler Fuel Augmentation with a Biomass Fired Atmospheric Circulating Fluid Bed Gasifier*, July 2001.

[132] <http://www.fosterwheeler.com/publications/tech_papers/powgen/bagasse3.cfm>

[133] OPET, "Review of Finnish Biomass Gasification Technologies, ESPOO, VVT:21, 2002.

[134] Granatstein, D.L.. "A Case Study- Waste Fueled Gasification Project – Greve in Chianti, Italy, CANMET;20, 2003. <http://www.ieabioenergy.com/ourwork.php?t=36#36>

[135] Morris, M., "Electricity Production from Solid Waste Fuels using Advanced Gasification Technology, Presented at SWANA's 1998/ISWA World Congress, Charlotte, North Carolina, 1998.

[136] Survey provided by Intellergy Corp., Berkeley, CA

[137] Galloway, T., Waidl, J., Annamalai, K., Sweeten, J., Tomlinson, T.L., Bellet, E.M., and Weigle, D., "Energy Resource Recovery Applications using Gasification and Steam Reforming," *IT3'02 Conference*, New Orleans, LA, May, 2002.

[138] <http://www.opas.no/company/technology.html>

[139] <http://www.opas.no/company/projects.html>

[140] Young B.C., Hauserman W.B., "X. Biomass energy conversion: conventional and advanced technologies," *Symposium on Development and Utilization of Biomass Energy Resources in Developing Countries*, 11–14 December 1995, Vienna, vol. I Thematic Papers, pp. 135–153, UNIDO.

[141] Klein, J., Lütge, C., Deutsch, M., Wischnewski, R., Mittelstädt, A., Vergasung von Restmüll nach dem PRECON-Verfahren auf Basis der Hochtemperatur-Winkler-Vergasung (HTW), Beiträge zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfällen und nachwachsenden Rohstoffen, 20–22. April 1998, Velen/Westfalen (Autorenmanuskripte), pp. 169–176, Hamburg: DGMK Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9802.

[142] Hein, K.R.G., Rep. ETDE-DE-965; DEOIG3639. Institut für Verfahrenstechnik und Dampfkesselwesen (IVD), Universität Stuttgart, Stuttgart, 2000.

[143] Adlhoch, W., Sato, H., Wolff, J., Radtke, K., "High-temperature Winkler gasification of municipal solid waste," *Gasification Technology Conference*, 8–11 October 2000, San Francisco, CA, 2000.

[144] Schiffer, H.P., Adlhoch, W., Meyer, B., "Die Wirbelschichtvergasung: Ein Verfahren zur rohstofflichen Verwertung von Restkunststoffen," *VGB Kraftwerkstechnik*, 1995, 75 (6), 523–528.

[145] Wischnewski, R., Mittelsta¨ dt, A., Renzenbrink, W., Lütge, C., Abraham, R., Merkmale und Vorzüge des Hochtemperatur-Winkler (HTW)-Verfahrens zur effzienten energetischen und stofflichen Nutzung von Abfällen, Beiträge zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfällen und nachwachsenden Rohstoffen, 20–22 April 1998, Velen/Westfalen (Autorenmanuskripte), pp. 143–150. DGMK Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9802, Hamburg.

[146] Lütge, C., Mork, M., Wischnewski, R., Mittelstädt, A., "Applying the High-Temperature-Winkler (HTW) gasification for processing solid wastes: The Krupp Uhde PreCon-process," *R'99 International Congress on Recovery, Recycling, Re-integration*, 2–5 February 1999, Geneva. Eidgenössisch Materialprü fungs- und Forschungsanstalt, St. Gallen.

[147] Greil, C., Hirschfelder, H., "XI. Circulating uidized-bed technologies for the conversion of biomass into energy," *Symposium on Development and Utilization of Biomass Energy Resources in Developing Countries*, 11–14 December 1995, Vienna, vol. I, "Thematic Papers," pp. 154–169, UNIDO.

[148] Krupp, U., "Energetische Verwertung von Abfa¨ llen." *BWK Brennstoff Warme Kraft*, Vol. 51 (1/2),1999, pp. 27–28.

[149] Adlhoch, W., Sato, H., Wolff, J., Radtke, K., "High-temperature Winkler gasification of municipal solid waste," *Gasification Technology Conference*, San Francisco, California, October, 2000.

[150] Dürrfeld, R., Abraham, R., Ein Holzgaskraftwerk mit motorischer Energieumwandlung auf Basis des Hochtemperatur-Winkler-Verfahrens (HTW), Beitr. age zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfa¨ llen und nachwachsenden Rohstoffen, April, 1998, Velen/Westfalen (Autorenmanuskripte), pp. 185–194, Hamburg: DGMK Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9802.

[151] Klein, J., Lütge, C., Deutsch, M., Wischnewski, R., Mittelstädt, A., Vergasung von Restmüll nach dem PRECON-Verfahren auf Basis der Hochtemperatur-Winkler-Vergasung (HTW), Beiträge zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfällen und nachwachsenden Rohstoffen, April, 1998, Velen/Westfalen (Autorenmanuskripte), pp. 169–176, Hamburg: DGMK Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9802.

[152] Wischnewski, R., Mittelstadt, A., Renzenbrink, W., Lutge, C., Abraham, R., Merkmale und Vorzuge des Hochtemperatur-Winkler (HTW)-Verfahrens zur effzienten energetischen und stofflichen Nutzung von Abfallen, Beitrage zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfa¨ llen und nachwachsenden Rohstoffen, April, 1998, Velen/Westfalen (Autorenmanuskripte), pp. 143–150. DGMK Deutsche Wissenschaftliche Gesellschaft fur Erdol, Erdgas und Kohle e.V. DGMK Tagungsbericht 9802, Hamburg.

[153] Klein, J., Lütge, C., Deutsch, M., Wischnewski, R., Mittelstädt, A., Vergasung von Restmüll nach dem PRECON-Verfahren auf Basis der Hochtemperatur-Winkler-Vergasung (HTW), Beiträge zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfällen und nachwachsenden Rohstoffen, April, 1998, Velen/Westfalen (Autorenmanuskripte), pp. 169–176, Hamburg: DGMK Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9802.

[154] Adlhoch, W., Sato, H., Wolff, J., Radtke, K., "High-temperature Winkler gasification of municipal solid waste," *Gasification Technology Conference*, San Francisco, California, October 2000.

[155] Anon, "New Bern Biomass to Energy Project Phase I: Feasibility Study," Rep. NREL/TP-421-7942 *National Renewable Energy Laboratory*, Golden, Colorado, 1995.

[156] Bucko, Z., Engelhard, J., Wolff, J., Vierrath, H., "400 MWe IGCC power plant with HTW gasification in the Czech republic," *Gasification Technology Conference*, San Francisco, California, October, 1999.

Bucko, Z., Takahasi, M., Vierrath, H. "HTW uidized-bed gasification for 400 MW IGCC power plant, Vresova—Czech Republic," *Gasification Technology Conference*, San Francisco, California, October 2000.

[157] Ibid.

[158] Dürrfeld, R., Abraham, R., Ein Holzgaskraftwerk mit motorischer Energieumwandlung auf Basis des Hochtemperatur-Winkler-Verfahrens (HTW), Beitr. age zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfa¨ llen und nachwachsenden Rohstoffen, April, 1998, Velen/Westfalen (Auto-T. Malkow / Waste Management 24 (2004) 53–79 73 renmanuskripte), pp. 185–194, Hamburg: DGMK Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9802.

[159] Wischnewski, R., et al., Merkmale und Vorzuge des Hochtemperatur-Winkler (HTW)-Verfahrens zur effzienten energetischen und stofflichen Nutzung von Abfallen, Beitrage zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfa¨ llen und nachwachsenden Rohstoffen, April, 1998, Velen/Westfalen (Autorenmanuskripte), pp. 143–150. DGMK Deutsche Wissenschaftliche Gesellschaft fur Erdol, Erdgas und Kohle e.V. DGMK Tagungsbericht 9802, Hamburg.

[160] Schiffer, H.P., Adlhoch, W., Meyer, B., "Die Wirbelschichtvergasung: Ein Verfahren zur rohstofflichen Verwertung von Restkunststoffen," *VGB Kraftwerkstechnik*, Vol. 75 (6), 1995, 523–528.

[161] Schiffer, H.P., Adlhoch, W., Sipila , K. (ed.), Korhonen, M. (ed.), "Gasification experience with biomass and wastes," *Seminar on Power Production from Biomass II with special Emphasis on Gasification and Pyrolysis R&DD*, March 1995.

[162] Schiffer H.P., et al., Beitragezur DGMK-Fachbereichstagung Energetische und stoffiche Nutzung von Abfallen und nachwachsenden Rohstoffen, April, 1996, Velen/Westfalen (Autorenmanuskripte), pp.

169–181. DGMK Deutsche Wissenschaftliche Gesellschaft fur Erdol, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9603, Hamburg.

[163] Hein, K.R.G., Rep. ETDE-DE-965; DEOIG3639, Institut für Verfahrenstechnik und Dampfkesselwesen (IVD), Universität Stuttgart, Stuttgart, 2000.

[164] Adlhoch, W., et al., "High-temperature Winkler gasification of municipal solid waste," *Gasification Technology Conference*, San Francisco, California, October, 2000.

[165] Anon, "New Bern Biomass to Energy Project Phase I: Feasibility Study," Rep. NREL/TP-421-7942 *National Renewable Energy Laboratory*, Golden, Colorado, 1995.

[166] Klein, J., et al., Vergasung von Restmüll nach dem PRECON-Verfahren auf Basis der Hochtemperatur-Winkler-Vergasung (HTW), Beiträge zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfällen und nachwachsenden Rohstoffen, April, 1998, Velen/Westfalen (Autorenmanuskripte), pp. 169–176, Hamburg: DGMK Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9802.

[167] Adlhoch, W., Sato, H., Wolff, J., Radtke, K., "High-temperature Winkler gasification of municipal solid waste," *Gasification Technology Conference*, San Francisco, California, October 2000.

[168] Bucko, Z., Engelhard, J., Wolff, J., Vierrath, H., "400 MWe IGCC power plant with HTW gasification in the Czech republic," *Gasification Technology Conference*, San Francisco, California, October2000.

[169] Bucko, Z., Takahasi, M., Vierrath, H., "HTW fluidized-bed gasification for 400 MW IGCC power plant, Vresova—Czech Republic," *Gasification Technology Conference*, San Francisco, California, October 2000.

[170] Dürrfeld, R., Abraham, R., Ein Holzgaskraftwerk mit motorischer Energieumwandlung auf Basis des Hochtemperatur-Winkler-Verfahrens (HTW), Beitrage zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfallen und nachwachsenden Rohstoffen, April, 1998, Velen/Westfalen (Auto-T. Malkow / Waste Management 24 (2004) 53–79 73 renmanuskripte), pp. 185–194, Hamburg: DGMK Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9802.

[171] Wischnewski, R., et al., Merkmale und Vorzuge des Hochtemperatur-Winkler (HTW)-Verfahrens zur effzienten energetischen und stofflichen Nutzung von Abfallen, Beitrage zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfa¨ llen und nachwachsenden Rohstoffen, April, 1998, Velen/Westfalen (Autorenmanuskripte), pp. 143–150. DGMK Deutsche Wissenschaftliche Gesellschaft fur Erdol, Erdgas und Kohle e.V. DGMK Tagungsbericht 9802, Hamburg.

[172] Schiffer, H.P., Adlhoch, W., Meyer, B., "Die Wirbelschichtvergasung: Ein Verfahren zur rohstofflichen Verwertung von Restkunststoffen," *VGB Kraftwerkstechnik*, Vol. 75, No. 6, 1995, 523–528.

[173] Schiffer, H.P., Adlhoch, W., Sipila, K. (ed.), Korhonen, M. (ed.), "Gasification experience with biomass and wastes," *Seminar on Power Production from Biomass II with special Emphasis on Gasification and Pyrolysis R&DD*, March 27–28, 1995.

[174] Schiffer H.P., et a.l., Beitragezur DGMK-Fachbereichstagung Energetische und stoffiche Nutzung von Abfallen und nachwachsenden Rohstoffen, April, 1996, Velen/Westfalen (Autorenmanuskripte), pp. 169–181. DGMK Deutsche Wissenschaftliche Gesellschaft fur Erdol, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9603, Hamburg.

[175] Hein, K.R.G., Rep. ETDE-DE-965; DEOIG3639, Institut für Verfahrenstechnik und Dampfkesselwesen (IVD), Universität Stuttgart, Stuttgart, 2000.

[176] Young B.C., Hauserman W.B., "X. Biomass energy conversion: conventional and advanced technologies," *Symposium on Development and Utilization of Biomass Energy Resources in Developing Countries*, December, 1995, Vienna, vol. I Thematic Papers, pp. 135–153, UNIDO.

[177] Anon, "New Bern Biomass to Energy Project Phase I: Feasibility Study," Rep. NREL/TP-421-7942 *National Renewable Energy Laboratory*, Golden, Colorado, 1995.

[178] Adlhoch, W., et al.,"High-temperature Winkler gasification of municipal solid waste," *Gasification Technology Conference*, San Francisco, California, October, 2000.

[179] Schiffer, H.P., Adlhoch, W., Meyer, B., "Die Wirbelschichtvergasung: Ein Verfahren zur rohstofflichen Verwertung von Restkunststoffen," *VGB Kraftwerkstechnik*, Vol. 75 (6), 1995, 523–528.

[180] Klein, J., et al., Vergasung von Restmüll nach dem PRECON-Verfahren auf Basis der Hochtemperatur-Winkler-Vergasung (HTW), Beiträge zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfällen und nachwachsenden Rohstoffen, April 1998, Velen/Westfalen (Autorenmanuskripte), pp. 169–176, Hamburg: DGMK Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9802.

[181] Adlhoch, W., et al., "High-temperature Winkler gasification of municipal solid waste," *Gasification Technology Conference*, San Francisco, California, October 2000.

[182] Adlhoch, W., et al., "High-temperature Winkler gasification of municipal solid waste," *Gasification Technology Conference*, San Francisco, California, October 2000.

[183] Wischnewski, R., Mittelstadt, A., Renzenbrink, W., Lutge, C., Abraham, R., Merkmale und Vorzuge des Hochtemperatur-Winkler (HTW)-Verfahrens zur effzienten energetischen und stofflichen Nutzung von Abfallen, Beitrage zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfa¨ llen und nachwachsenden Rohstoffen, April, 1998, Velen/Westfalen (Autorenmanuskripte), pp. 143–150. DGMK Deutsche Wissenschaftliche Gesellschaft fur Erdol, Erdgas und Kohle e.V. DGMK Tagungsbericht 9802, Hamburg.

[184] MLEE, *Umwelt Technologie Aktuell*, Vol. 6, No. 3, 1995, 229–232.

[185] Faulstich, M., and Bilitewski, B., Faulstich, M., Urban, A., eds., "Rückstände aus der thermischen Abfallbehandlung-und Verwertungsverfahren im Überblick," *Thermische Restabfallbehandlung, Abfallwirtschaft in Forschung und Praxis, Band 38*, Erich Schmidt Verlag, Berlin, 1996, pp. 261–296.

[186] Redepenning, H., Kremer, H., Rizzon, H., Das PyroMelt-Verfahren, Beitr. age zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfällen und nachwachsenden Rohstoffen, April, 1996, Velen/Westfalen (Autorenmanuskripte), pp. 151–158. DGMK Deutsche Wissenschaftliche, Hamburg. Gesellschaft für Erdöl, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9603; ETDE-DE-576.

[187] Heermann, C., et al., *Pyrolysis & Gasification of Waste: A worldwide technology and business review*, Juniper Consultancy Services LTD, 2001.

[188] JSIM, 1996b. Melting furnace system for sewage sludge. <http://nett21.unep.or.jp/JSIM_DATA/WASTE/WASTE_5/html/Document_420.html%>

[189] GEC, "Melting furnace system for sewage sludge," 1996.

<http://nett21.unep.orjp/CTT_DATA/WATER/WATER_4/html/Water-211.html>

[190] Faulstich, M., and Bilitewski, B., Faulstich, M., Urban, A., eds., “Rückstände aus der thermischen Abfallbehandlung-und Verwertungsverfahren im Überblick,” *Thermische Restabfallbehandlung, Abfallwirtschaft in Forschung und Praxis, Band 38*, Erich Schmidt Verlag, Berlin, 1996, pp. 261–296.

[191] Johnke, B., Gamer, “First draft of a German report with basic informations for a brief-document waste incineration,” Rep. UBA, Saxon Ministry of State for Environment and Agriculture; FEAD; ITAD; VCI; VGB Power; VDI; ATV; VDMA; FDBR, 2001.

[192] Redepenning, H., Kremer, H., Rizzon, H., Das PyroMelt-Verfahren, Beitr. age zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfällen und nachwachsenden Rohstoffen, April, 1996, Velen/Westfalen (Autorenmanuskripte), pp. 151–158. DGMK Deutsche Wissenschaftliche, Hamburg. Gesellschaft für Erdöl, Erdgas und Kohle e.V. DGMK-Tagungsbericht 9603; ETDE-DE-576.

[193] Schingnitz, M., Gröz, J., “Flugstromvergasung Vergasung von. Brenn, Rest und Abfallstoffen,” Umwelt, 1999, 9, 48–51.

[194] GOM Antwerp, 1999 <http://www.gomantwerpen.be/nederlands/publicaties/afvaloud/studieafv19-05-99.html>

[195] Barin, I., Igelbu¨ scher, A., Zenz, F.R., and Bilitewski, B., Faulstich, M., Urban, A., eds., “Thermodynamische Analyse der Verfahren zur thermische Entsorgung von Müll,” *Thermische Restabfallbehandlung, Abfallwirtschaft in Forschung und Praxis,Band 38*, 1996, Erich Schmidt Verlag, Berlin, pp. 188–206.

[196] Reimert, R., Setzer, U., “Die Mullvergasung, Mullverbrennungeine Verfahrensu¨ bersicht,” *GWF Gas Wasser Fach Gas Erdgas*, Vol. 137 (2), 1996, 60–69.

[197] Heil, J., Simons, D.U., and Bilitewski, B., Faulstich, M., Urban, A., eds., “Konventionelle und neue thermische Verfahren im Vergleich,” *Thermische Restabfallbehandlung, Abfallwirtschaft in Forschung und Praxis, Band 38,* 1996, Erich Schmidt Verlag, Berlin, pp. 228 – 252.

[198] Kempin, T., Faulstich, M.; and Bilitewski, B., Urban, A., eds., “Verfahrensüberblick und-auswahl aus der Sicht des Betreibers; Wirbelschichtfeuerung-eine Alternative zur Rostfeuerung,” *Thermische Restabfallbehandlung, Abfallwirtschaft in Forschung und Praxis, Band 38*, Erich Schmidt Verlag, Berlin, pp. 207–227.

[199]Lamp, P., Reichel, A., Ziegler, F., Warmer. uckgewinnung bei Anlagen zur Kla¨ rschlammvergasung, Beitra¨ ge zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfa¨ llen und nachwachsenden Rohstoffen, April, 1996, Velen/Westfalen (Autorenmanuskripte), pp. 393–400, Hamburg: DGMK Deutsche Wissenschaftliche Gesellschaft fu¨ r Erdo¨ l, Erdgas und Kohle e.V. DGMK- Tagungsbericht 9603; ETDE-DE-576.

[200] Tauber, C., “Thermische Restm. ullbehandlung heute Rostfeuerung, Schwel-Brenn-, Thermoselect- und Konversions-Verfahren.” *Energiewirtschaftliche Tagesfragen*, Vol. 45, No. 6, 1995, pp. 378–385.

[201] Schingnitz, M., Göhler, P. Der Einsatz niederkaloriger Energieträger aus Reststoffen und Bioabfällen zur Synthesegaserzeugung nach dem Noell Konversionsverfahren, Beiträge zur DGMKFachbereichstagung Energetische und stoffiche Nutzung von Abfällen und nachwachsenden Rohstoffen, April, 1996, Velen/ Westfalen (Autorenmanuskripte), pp. 69–78, DGMK Deutsche Wissenschaftliche Gesellschaft für Erdöol, Erdgas und Kohle e.V. DGMK- Tagungsbericht 9603; ETDE-DE-576, Hamburg.

[202] Faulstich, M.; and Bilitewski, B., Faulstich, M., Urban, A., eds., “Rückstände aus der thermischen Abfallbehandlung-und Verwertungsverfahren im Überblick,” *Thermische Restabfallbehandlung, Abfallwirtschaft in Forschung und Praxis, Band 38*, Erich Schmidt Verlag, Berlin, pp. 261–296, 1996.

[203] Jaeger, M., Mayer, M., “The Noell Conversion Process-a gasification process for the pollutant-free disposal of sewage sludge and the recovery of energy and materials,” *Water Science and Technology*, Vol. 41, No. 8, 2000, 37–44.

[204] Lorson, H., Schingnitz, M., “Konversionsverfahren zur thermischen Verwertung von Rest- und Abfallstoffen,” *BWK Brennstoff Warme Kraft*, Vol. 46, No. 5, 1994, 214–217.

[205] Leipnitz, Y., Ponto, H.U., “The Noell conversion process for residual waste gasification,” *Modern Power Systems*, Vol. 16, No. 5, 1996, 29–32.

[206] Richers et al., Programm zur Untersuchung thermischer Behandlungsanlagen fur Siedlungsabfall, Wissenschaftliche Berichte FZKA 6298, Forschungszentrum Karlsruhe GmbH, Karlsruhe, 1999.

[207] Schingnitz M., Görz J., Kurzfassungen der DECHEMA-Jahrestagungen 1998, pp. 26–28. Mai 1998, Wiesbaden, vol. II, p. 331, Dechema e.V, Frankfurt/M.

[208] Schingnitz, M., Seidel, W., Vergasung von Rest- und Abfallstoffen nach Noell-Technologien, 13. Fachseminar des Zentrum füurAbfallforschung der TU Braunschweig Stoffstromspezifische im Hinblick auf thermische Verfahren, 24–25. September 1998, Braunschweig, pp. 175–203.Technische Universität Braunschweig, Braunschweig.

[209] Lorson, H., Schingnitz, M., “Konversionsverfahren zur thermischen Verwertung von Rest- und Abfallstoffen,” *BWK Brennstoff Wa¨ rme Kraft*, Vol. 46, No. 5, 1994, pp. 214–217.

[210] Heermann, C., et al., *Pyrolysis & Gasification of Waste: A worldwide technology and business review*, Juniper Consultancy Services LTD, 2001.

[211] Richers et al., Programm zur Untersuchung thermischer Behandlungsanlagen fur Siedlungsabfall, Wissenschaftliche Berichte FZKA 6298, Forschungszentrum Karlsruhe GmbH, Karlsruhe, 1999.

[212] Leipnitz, Y., Ponto, H.U., “The Noell conversion process for residual waste gasification,” *Modern Power Systems*, Vol. 16, No. 5, 1996, pp. 29–32.

[213] Schingnitz, M., et al., “Gasifier to convert nitrogen waste organics at Seal Sands, UK,” *Gasification Technology Conference*, San Francisco, California, October 2000.

[214] Gaudig, U., “Experience during erection and commissioning the gasification plant,” Seal Sands, UK. *Gasification Technology Conference*, San Francisco, California, October 2000.

[215] Jaeger, M., Mayer, M., “The Noell Conversion Process—a gasification process for the pollutant-free disposal of sewage sludge and the recovery of energy and materials,” *Water Science and Technology*, Vol. 41, No. 8, 2000, pp. 37–44.

[216] Lorson, H., Schingnitz, M., “Konversionsverfahren zur thermischen Verwertung von Rest- und Abfallstoffen,” *BWK Brennstoff Warme Kraft*, Vol. 46, No. 5, 1994, pp. 214–217.

[217] Leipnitz, Y., Ponto, H.U., “The noell conversion process for residual waste gasification,” *Modern Power Systems*, Vol. 16, No. 5, 1996, pp. 29–32.

[218] BBP, 2002b, Verfahrenstechnische Anlage Northeim, <http://www.noell.de/ energie_1/north.htm>

[219] Richers et al., Programm zur Untersuchung thermischer Behandlungsanlagen fur Siedlungsabfall, Wissenschaftliche Berichte FZKA 6298, Forschungszentrum Karlsruhe GmbH, Karlsruhe, 1999.

[220] Young B.C., Hauserman W.B., "X. Biomass energy conversion: conventional and advanced technologies," *Symposium on Development and Utilization of Biomass Energy Resources*

in Developing Countries, December, 1995, Vienna, Vol. I, Thematic Papers, pp. 135–153, UNIDO

[221] Paisley, M.A., et al., and Overend R.P., Chornet E., eds., "Commercial development of the Battelle/FERCO biomass gasification process initial operation of the McNeil gasifier," *Third Biomass Conference of the Americas Making a Business from Biomass in Energy, Environment, Chemicals, Fibers and Materials*, August 24–29, 1997, Montreal, Vol. 1, pp. 579–588, Pergamon

Paisley, M.A., Litt, R.D., Creamer, K.S., "Gasification of refuse derived fuel in a high throughput gasification system," *15th annual conference of the Institute of Gas Technology ENERGY FROM BIOMASS AND WASTES XIV*, January 29–February 2, 1990, Lake Buena Vista, Florida, *Institute for Gas Technology*, Chicago, Illinios.

Paisley, M.A., et al., "Preliminary operating results from the Battelle/FERCO gasification demonstration plant in Burlington, Vermont, USA," *1st World Conference and Exhibition on Biomass for Energy and Industry*, June 5–9, 2000, Seville

Paisley, M.A., Irving, J.M., Overend, R.P., "A promising power option-the FERCO Silvagas biomass gasification process—operating experience at the Burlington gasifier," *ASME Turbo Expo Land, Sea, & Air 2001*, June 4–7, 2001, New Orleans, LA, *American Society of Mechanical Engineers*, New York.

[222] Ibid.

[223] Ibid.

[224] Ibid.

[225] Overend, R., "Biomass gasification: the enabling technology," *Renewable Energy World* (9/10), 2000.

[226] Farris, M.,et al.; and Sipil. a. K., Korhonen M., eds., "The Battelle/ FERCO biomass gasification process design, engineering, construction, and startup phase," *Seminar on Power production from biomass III. Gasification and pyrolysis R&D&D for industry*, 14–15 September, 1998, Espoo, pp. 87–101, Espoo: VTT. VTT Symposium 192.

[227] Bain R.L., Overend R.P., Craig K.R., "Biomass-fired power generation," *Engineering Foundation Conference Biomass Usage for Utility and Industrial Power*, April 29–May 3, 1997, Snowbird, Utah, Engineering Foundation.

[228] Bain, R.L., Overend, R.P., "New gasification technology offers promise for biomass plants," *Power Engineering*, Vol. 100, No. 8, 1996, pp. 32–39.

[229] Kinoshita, C.M., Turn, S.Q., Overend, R.P., Bain, R.L., "Power generation potential of biomass gasification systems," *58th American Power Conference*, 9–11 April, 1996, Chicago, Illionis, Vol. 1, pp. 727–732. Illinois Institute of Technology, Chicago, Illinois.

Kinoshita, C.M., Turn, S.Q., Overend, R.P., Bain, R.L., "Power generation potential of biomass gasification systems," *Journal of Energy Engineering*, Vol. 123, No. 3, 1997, pp. 88–99.

[230] Ibid.

[231] Overend, R.P., Rivard, C.J.; and Klass, D.L. ed., "Thermal and biological gasification," *1st Biomass Conference of the Americas: Energy, Environment, Agriculture and Industry*, August 30–September 2, 1993, Burlington, Vermont, Vol. I. National Renewable Energy Laboratory, Golden, Colorado, pp. 470–497. NREL/CP-200-5768.

[232] Overend, R.P., Kinoshita, C.M., Antal, M.J. Jr., "Bioenergy in transition," *Journal of Energy Engineering*, Vol.122, No. 3, 1996, pp. 78–92.

[233] Overend, R.P., Costello, R., "Bioenergy in North America: An overview of liquid biofuels, electricity, and heat," *10th European Bioenergy Conference and Technology Exhibition*, June 8–11, 1998, Wurzburg, pp. 59–61. C.A.R.M.E.N. e.V., Rimpar

[234] Paisley, M.A., "Gas turbine power generation using a high throughput biomass gasification system," *29th Intersociety Energy Conversion Engineering Conference*, August 7–11, 1994, Monterey, California, Vol. 4, pp. 1555–1560, *American Institute for Aeronautics and Astronautics*, AIAA-94-4009-CP, Reston, Virginia.

[235] Paisley, M.A., Anson, D., "Biomass gasification for gas turbinebased power generation. Transactions of the ASME," *Journal of Engineering for gas Turbine and Power*, Vol. 120, No 2, 1998, pp. 284–288.

[236] Anon, "New Bern Biomass to Energy Project Phase I: Feasibility Study," Rep. NREL/TP-421-7942 *National Renewable Energy Laboratory*, Golden, Colorado, 1995.

[237] Paisley, M.A., et al.; and Overend R.P., Chornet E., eds., "Commercial development of the Battelle/FERCO biomass gasification process initial operation of the McNeil gasifier," *Third Biomass Conference of the Americas Making a Business from Biomass in Energy, Environment, Chemicals, Fibers and Materials*, August 24–29, 1997, Montreal, Vol. 1, pp. 579–588, Pergamon.

[238] Paisley, M.A., et al.; and Overend, R.P., Chornet, E., eds., "Commercial development of the Battelle/FERCO biomass gasification process initial operation of the McNeil gasifier," *Third Biomass Conference of the Americas Making a Business from Biomass in Energy, Environment, Chemicals, Fibers and Materials*, August 24–29, 1997, Montreal, vol. 1, pp. 579–588, Pergamon.

Paisley, M.A., Litt, R.D., Creamer, K.S., "Gasification of refuse derived fuel in a high throughput gasification system," *15th annual conference of the Institute of Gas Technology ENERGY FROM BIOMASS AND WASTES XIV*, January 29–February 2, 1990, Lake Buena Vista, Florida, *Institute for Gas Technology*, Chicago, Illinois.

[239] Paisley, M.A., et al.; and Overend, R.P., Chornet E., eds., "Commercial development of the Battelle/FERCO biomass gasification process initial operation of the McNeil gasifier," *Third Biomass Conference of the Americas Making a Business from Biomass in Energy, Environment, Chemicals, Fibers and Materials*, August 24–29, 1997, Montreal, Vol. 1, pp. 579–588, Pergamon.

Paisley, M.A., Litt, R.D., Creamer, K.S., "Gasification of refuse derived fuel in a high throughput gasification system," *15th annual conference of the Institute of Gas Technology ENERGY FROM BIOMASS AND WASTES XIV*, January 29–February 2, 1990, Lake Buena Vista, Florida, *Institute for Gas Technology*, Chicago, Illinois.

[240] Piggin, P.R., "Clinical incineration—a viewpoint," *Health Estate Journal,* Vol. 44, No. 5, 1990, pp. 21–22.

[241] Anon, "New Bern Biomass to Energy Project Phase I: Feasibility Study," Rep. NREL/TP-421-7942 *National Renewable Energy Laboratory*, Golden, Colorado, 1995.

[242] Paisley, M.A., et al.; and Overend, R.P., Chornet E., eds., "Commercial development of the Battelle/FERCO biomass gasification process initial operation of the McNeil gasifier," *Third Biomass Conference of the Americas Making a Business from Biomass in Energy, Environment, Chemicals, Fibers and Materials*, August 24–29, 1997, Montreal, Vol. 1, pp. 579–588, Pergamon.

[243] Paisley, M.A., et al., and Overend, R.P., Chornet E., ed., "Commercial development of the Battelle/FERCO biomass gasification process initial operation of the McNeil gasifier," *Third Biomass Conference of the Americas Making a Business from Biomass in Energy, Environment, Chemicals, Fibers and Materials*, August, 24–29, 1997, Montreal, Vol. 1, pp. 579–588, Pergamon.

[244] Piggin, P.R., "Clinical incineration—a viewpoint," *Health Estate Journal,* Vol. 44, No. 5, 1990, 21–22.

[245] Niessen, W.R.., Markes, C.H., Sommerlad, R.E., "Evaluation of Gasification and Novel Thermal Processes for the Treatment of Municipal Solid Waste (Rep. NREL/TP-430-21612)," National Renewable Energy Laboratory, Golden, Colorado, 1996.

[246] Williams, R.B., and Jenkins, B.M. "Technology Assessment for Biomass Power Generation". Task 1.1.1 Report, SMUD ReGen Program. PIER Contract 500-00-034

[247] DOE, 2002, <http://www.eren.doe.gov/biopower/projects/ia_tech_gas4.htm>

[248] Nitsche, R., Mallon, J., Scheidig, K., Sauerstoff-Schmelz-Vergasung zur Verwertung von Abfa¨ llen. Wasser Luft Boden Vol. 45, No. 6, 2001, pp. 57–60.

[249] Faulstich, M.; and Bilitewski, B., Faulstich, M., Urban, A., eds., "Rückstände aus der thermischen Abfallbehandlung-und Verwertungsverfahren im Überblick," *Thermische Restabfallbehandlung, Abfallwirtschaft in Forschung und Praxis, Band 38*, Erich Schmidt Verlag, Berlin, pp. 261–296, 1996.

[250] Larsen, E.D., et al., "Intelligent control of cupola melting," *Australia-Pacific Forum on Intelligent Processing and Manufacturing of Materials*, July 14–16, 1997, Sydney

[251] Moore, K.L., Larsen, E., Clark, D., "Experimental control of a cupola furnace," *1998 American Controls Conference*, June 24–26, 1998, Philadelphia, Pennyslvania.

[252] Abdelrahman, M.A., Moore, K.L., "Optimal choice of cupola furnace nominal operating point," *30th IEEE Southeastern Symposium on Systems Theory*, March 8–10, 1998, Morgantown, West Virginia, IEEE, Piscataway, New Jersey.

[253] Nitsche, R., Mallon, J., Scheidig, K., "Sauerstoff-Schmelz-Vergasungzur Verwertung von Abfallen," *Wasser Luft Boden,* Vol. 45, No. 6, 2001, 57–60.

[254] Ibid.

[255] Heermann, C., F. J. Schwager, et al., *Pyrolysis & Gasification of Waste: A worldwide technology and business review*, Juniper Consultancy Services LTD, 2001.

[256] Steedman W.G., 2001. <http://www.lanl.gov/projects/cctc/factsheets/pcdq/pulsecomdemo.html>

[257] Young B.C., Hauserman W.B., "X. Biomass energy conversion: conventional and advanced technologies," *Symposium on Development and Utilization of Biomass Energy Resources in Developing Countries*, December 11–14, 1995, Vienna, Vol. I Thematic Papers, pp. 135–153, UNIDO.

[258] Niessen, W.R., Advanced thermal processing alternatives for solid waste management. Proceedings of the Fifth Annual North American Waste-to-Energy Conference, April 22–25, 1997, Research Triangle Park, North Carolina, pp. 103–125. CONF-970440, DE97007054, GRWTE-0105; Solid Waste Association of North America, Silver Spring, Maryland; Air and Waste Management Association, Pittsburgh, Pennsylvania; Integrated Waste Services Association, Washington, D.C.; National Renewable Energy Lab., Golden, Colorado; American Society of Mechanical Engineers, Yonkers, New York; Solid Waste Processing Div.; Environmental Protection Agency, Research Triangle Park, North Carolina; Air Pollution Technology Branch.

[259] Niessen, W.R., Markes, C.H., Sommerlad, R.E., "Evaluation of Gasification and Novel Thermal Processes for the Treatment of Municipal Solid Waste (Rep. NREL/TP-430-21612)," National Renewable Energy Laboratory, Golden, Colorado, 1996.

[260] Anon, "New Bern Biomass to Energy Project Phase I: Feasibility Study," Rep. NREL/TP-421-7942 *National Renewable Energy Laboratory*, Golden, Colorado, 1995.

[261] Mansour, M.N.; and Hall, D.O., Grassi, G., Scheer, H., eds., "Mtci biomass steam reforming technology," *Proceedings of the 7th E.C. Conference on Biomass for Energy and Industry*, October 5–9, 1992, Florence, Ponte Press, Bochum, pp. 199–204.

[262] Anon., "Pulse Combustor Design Qualification Test," *Industrial Applications Program Update 2000,* 2000e.

[263] Robinson, V., Rockvam, L., "Black liquor steam reforming/pulsed combustion," *Forest Products Project Fact Sheet*, Office of Industrial Technologies, Energy Efficiency and Renewable Energy. U.S. DOE, Washington, D.C., 1999.

[264] Robinson, V., DeCarrera, R., "Engineering study for a full scale demonstration of steam reforming black liquor gasification at Georgia-Pacific's mill in Big Islands, Virginia," *Forest Products Project Fact Sheet*, Office of Industrial Technolgies, Energy Efficiency and Renewable Energy, U.S. DOE, Washington, D.C., 2001.

[265] Mansour, M.N.; and Hall, D.O., Grassi, G., Scheer, H., eds., "Mtci biomass steam reforming technology," *Proceedings of the 7th E.C. Conference on Biomass for Energy and Industry*, October 5–9, 1992, Florence, Ponte Press, Bochum, pp. 199–204.

[266] Niessen, W.R., Advanced thermal processing alternatives for solid waste management. Proceedings of the Fifth Annual North American Waste-to-Energy Conference, April 22–25, 1997, Research Triangle Park, North Carolina, pp. 103–125. CONF-970440, DE97007054, GRWTE-0105; Solid Waste Association of North America, Silver Spring, Maryland; Air and Waste Management Association, Pittsburgh, Pennsylvania; Integrated Waste Services Association, Washington, D.C.; National Renewable Energy Lab., Golden, Colorado; American Society of Mechanical Engineers, Yonkers, New York; Solid Waste Processing Div.; Environmental Protection Agency, Research Triangle Park, North Carolina; Air Pollution Technology Branch.

[267] Steedman W.G., 2001. <http://www.lanl.gov/projects/cctc/factsheets/pcdq/pulsecomdemo.html>

[268] Niessen, W.R., Advanced thermal processing alternatives for solid waste management. Proceedings of the Fifth Annual North American Waste-to-Energy Conference, April 22–25, 1997, Research Triangle Park, NC, pp. 103–125. CONF-970440, DE97007054, GRWTE-0105; Solid Waste Association of North America, Silver Spring, Maryland; Air and Waste Management Association, Pittsburgh, Pennsylvania; Integrated Waste Services Association, Washington, D.C.; National Renewable Energy Lab., Golden, Colorado; American Society of Mechanical Engineers, Yonkers, New York; Solid Waste Processing Div.; Environmental Protection Agency, Research Triangle Park, North Carolina; Air Pollution Technology Branch.

[269] Niessen, W.R., Markes, C.H., Sommerlad, R.E., "Evaluation of Gasification and Novel Thermal Processes for the Treatment of Municipal Solid Waste (Rep. NREL/TP-430-21612)," National Renewable Energy Laboratory, Golden, Colorado. 1996.

[270] Anon, "New Bern Biomass to Energy Project Phase I: Feasibility Study, Rep. NREL/TP-421-7942 *National Renewable Energy Laboratory*, Golden, Colorado, 1995.

[271] Anon., "Pulse Combustor Design Qualification Test," *Industrial Applications Program Update 2000,* 2000e.

[272] Robinson, V., DeCarrera, R., “Engineering study for a full scale demonstration of steam reforming black liquor gasification at Georgia-Pacific’s mill in Big Islands, VA,” *Forest Products Project Fact Sheet*, Office of Industrial Technologies, Energy Efficiency and Renewable Energy, U.S. DOE, Washington, D.C., 2001.

[273] Robinson, V., Rockvam, L., “Black liquor steam reforming/pulsed combustion,” *Forest Products Project Fact Sheet*, Office of Industrial Technologies, Energy Efficiency and Renewable Energy. U.S. DOE, Washington, D.C., 1999.

[274] Mansour, M.N.; and Hall, D.O., Grassi, G., Scheer, H., eds., “Mtci biomass steam reforming technology,” *Proceedings of the 7th E.C. Conference on Biomass for Energy and Industry*, October 5–9, 1992, Florence, Ponte Press, Bochum, pp. 199–204.

[275] Ibid.

[276] ELECTROFARMING, Das ELECTROFARMING Konzept Dezentrale Kogeneration von Wasserstoff, Strom und Wa¨ rme aus Biomasse, EF Electro-Farming Energie- und Umwelttechnik GmbH, Grobberghofen, 2002.

[277] Johnssen, W.G., ELECTRO-FARMING Das ELECTROFARMING Konzept Dezentrale Kogeneration von Wasserstoff, Strom und Wärme aus Biomasse, EF Electro-Farming Energie- und Umwelttechnik GmbH, Grobberghofen, 2002.

[278] ECS, *Strom, Wärme und Wasserstoff aus Biomasse Entwicklung für das nächste Jahrtausend,* 2002. <http://www.hp-netline.com/umweltreport/Dresden_2001/biomasse.html>

[279] Anon, “New Bern Biomass to Energy Project Phase I: Feasibility Study,” Rep. NREL/TP-421-7942 *National Renewable Energy Laboratory*, Golden, Colorado, 1995.

[280] Henderson, P., “The meltguard corrosion probe and field test experience (Rep. M9-820),” *Stiftelsen för Värmeteknisk Forskning*, Stockholm, 2001.

[281] Wolf, B., Meyer, B., Verfahrenstechnik und Hauptausru¨ stungen der mehrstufligen Vergasung von Kohle und Biomasse nach dem Carbo-V-Verfahren, Beitra¨ ge zur DGMK-Fachbereichstagung Energetische und stoffliche Nutzung von Abfa¨ llen und nachwachsenden Rohstoffen, April 10–12 2000, Velen/Westfalen, pp. 205–212. DGMK Deutsche Wissenschaftliche Gesellschaft fur Erdo l, Erdgas und Kohle e.V. DGMK-Tagungsberich, 2000-1, Hamburg, 2000.

[282] Ibid.

[283] Whiting, K.J.; and Barnow, L.M., Dempsey, C.R., Tripodes, J.G. eds., “The thermal conversion of solid wastes to energy by the production of high cv fuel gas,” *Proceedings Internat ional Incineration Conference on Thermal Treatment of Radioactive, Hazardous Chemical, Mixed Munitions, and Pharmaceutical Wastes*, May 8–12, 1995, Bellevue, Washington, University of California, Irvine, California, pp. 705–708.

[284] Lawson, D., Grimshaw, T., “Gasification of dried sewage sludge and associated screenings,” *Euroforum Boues Sludge Conference*, November 23–24, 1999, Paris.

[285] Lawson, D., “Application of the WGT process for small scale MSW plant,” *Institute for Waste Management Thermal Treatment Seminar*, March, 2000a.

[286] Lawson, D., *The UK potential for small scale municipal waste gasification/pyrolysis plant: A Workshop Seminar,* organized by M.E.L Research, funded by ETSU, 2000b.

[287] WGT, 2002c, <http://www.wgtuk.com/ukindex.html>

[288] WGT, 2002a, <http://www.wgtuk.com/schematic.jpg>

[289] WGT, 2002b, <http://www.wgtuk.com/ukcommercial%20-plant.html>

[290] <http://www.heuristicengineering.com>, also personal communication with Malcom Lefcort of Hueristic Engineering Inc., British Columbia, Canada.

[291] Towill-Corporation, R. M., "New Systems Research for Refuse Disposal- Oahu Municipal Refuse Disposal Alternatives Study," City&County of Honolulu, Honolulu, 2000.

[292] Scott Turn & Charles Kinoshita, Natural Energy Institute, University of Hawaii, 2004.

[293] Themelis, N. J., Kim, Y. H., and Brady, M. H., "Energy recovery from New York City municipal solid wastes," *Waste Management & Research*, Vol. 20, No. 3, 2002, pp. 223–233.

[294] Carter, G. W., and Tsangaris, A., "Municipal solid waste disposal process," U.S. Patent Number 5280757, 1994.

[295] <http://www.rcl-plasma.com/overview.htm#2.3.%20Plasma%20System%20Description> (March 17, 2004).

[296] Scott Turn & Charles Kinoshita, Natural Energy Institute, University of Hawaii, 2004.

[297] Dighe, S. V., and Lazzaria, D., "Westinghouse plasma gasification technology for coal and co-fired coal/biomass gasification," *Pittsburgh Coal Conference,*. 2002.

[298] 2003 WTERT Fall meeting,. Columbia University, <http://www.seas.columbia.edu/earth/wtert/meet2003/wtert-2003_finstein.pdf> (Feb. 27, 2004).

[299] <http://www.arrowecology.com>

[300] Grady, C. P. L., Daigger, G. T., and Lim, H. C., *Biological wastewater treatment, 2nd edition*, Marcel Dekker, New York, 1999.

[301] Zhang, R., and Zhang, Z., "Biogasification of solid waste with an anaerobic-phased solids-digester system," U.S. Patent No. 6,342,378, Regents of the University of California, USA, 2002.

[302] Zhang, R. H., and Zhang, Z. Q., "Biogasification of rice straw with an anaerobic-phased solids digester system," *Bioresource Technology*, Vol. 68, No. 3, 1999, pp. 235–245.

[303] Fruteau de Laclos, Desbois, et al., 1997.

[304] Verma, S., "Anaerobic digestion of biodegradable organics in municipal solid wastes, " *Earth Resources Engineering*, New York, Columbia University**, Vol.** 56, 2002 <http://www.steinmuller-valorga.fr/index_en.php>.

[305] Verma, 2002.

[306] Farneti, Cozzolino et al., 1999.

[307] <http://www.citec.fi/lang/eng/enviroment/Waasa_process/Ref_biogas.pdf>

[308] Verma, 2002.

[309] <http://www.iska-gmbh.de/allgemeine%20grafiken/iska_engl.pdf>

[310] <http://www.grd.com.au/index.php?c=global&article_id=314>

[311] <http://www.wme.com.au/categories/waste_managemt/dec1_02.>

[312] <http://www.casa2000.net/wsludgewabioplants.htm>

[313] <http://www.undp.org.in/programme/GEF/september/page16-20.htm>

[314] Verma, 2002.

[315] <http://www.ows.be/>